Drought risk for water supply systems based on low-flow regionalisation

Dissertation

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*) Either the German or the Italian form of the title may be used.

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ABSTRACT

This work focuses on low flow indices that are commonly evaluated at gauged sites from observed streamflow time series. Hydrological data are not always available at the site of interest: regional frequency analysis is commonly used for the estimation of flows at sites where little or no data exists. The study is applied to Tuscany rivers discharge dataset, recorded from 1949 to 2008. The area is subdivided into homogeneous regions using an L-moments procedure. The low flow indices are evaluated with deterministic and geostatistical methods. A multivariate model, based on geomorphoclimatic characteristics, is also assessed. For each sub-region a relation connecting low flow indices and geomorphoclimatic characteristics is found.

Drought indices show little correlation with water shortage situations that depend also on water storage, demand fluctuation and on the actions carried out to reduce drought effects. For that reason an indicator relating supply and demand is required in order to identify situations of risk of water shortages. An analysis of the relationship between failure of water supply systems and reservoir volumes for the area of Firenze, is performed using Monte Carlo simulations. The reservoir levels and volumes are simulated using time series of the period 1970-2005. Four scenarios (i.e. normal, pre-alert, alert and emergency) associated with different levels of severity of drought are defined. Threshold values are identified considering the probability to assure a given fraction of the demand in a certain time horizon, and are calibrated with an optimization method, which try to minimize the water shortages, especially the heavier. The critical situations are assessed month by month in order to evaluate optimal management rules during the year and avoid conditions of total water shortage.

KURZFASSUNG

Die vorliegende Arbeit konzentriert sich auf Niedrigwasserindices, die im Allgemeinen mit Hilfe von an geeichten Anlagen beobachteten Abflusszeitreihen bewertet werden. Hydrologische Daten sind für die betreffenden Anlagen nicht immer verfügbar: regionale Frequenzanalysen werden meist für die Strömungsschätzung derjenigen Anlagen verwendet, für welche keine oder nur wenige Daten vorliegen. Die Studie bezieht sich auf zwischen 1949 und 2008 aufgezeichnete Abflussdatensätze toskanischer Flüsse. Das Gebiet wird unter Anwendung der L-Moment-Methode in homogene Regionen unterteilt und die Indices werden anhand deterministischer und geostatistischer Methoden ausgewertet. Darüber hinaus wird ein multivariates auf geomorphoklimatischen Eigenschaften basierendes Modell untersucht. Für jede Subregion wird das Verhältnis zwischen Indices und geomorphoklimatischen Eigenschaften aufgezeigt.

Dürreindices zeigen eine geringe Korrelation mit Wassermangelsituationen , die durch Staumaßnahmen, Nachfrageschwankungen sowie Maßnahmen zur Reduzierung von Dürreeffekten ausgelöst werden. Daher ist ein Indikator notwendig, der Angebot und Nachfrage ins Verhältnis setzt, um das Risiko von Wassermangelsituation bestimmen zu können. Mittels Monte-Carlo-Simulationen wird die Beziehung zwischen dem Versagen von Wasserversorgungssystemen und Reservevolumen für das Gebiet Florenz analysiert. Unter Verwendung der Zeitreihen zwischen 1970 und 2005 werden Reserveniveaus und -volumen simuliert. Dabei werden vier verschiedene Szenarien bezüglich Schweregrade der Dürre definiert. Es werden Grenzwerte identifiziert, um eine bestimmte Nachfrage in einem bestimmten Zeithorizont zu gewährleisten. Diese werden dann mittels einer Optimierungsmethode kalibriert, die versucht v.a. schwerere Wassermangelsituationen zu minimisieren. Die kritischen Situationen werden Monat für Monat untersucht, um über das Jahr optimale Managementregeln aufzuzeigen, die Situationen totalen Wassermangels zu vermeiden helfen.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Description	Unit
a_i	i-th parameter in Multivariate Analysis	
AM(*n*-day)	smallest average discharge of n consecutive days within one year	m^3/s
B	number of times the process went into failure	
cr	correlation coefficient between stations	
D_i	Discordancy at i site	
d_i	deficit level	
Ev	daily evaporation	mm
f_i	prescribed function values at the scatter points	
FP	flow length	km
H1	Heterogeneity for *L-cv* scatter	
H2	Heterogeneity for *L-cv*–*L-sk*	
H3	Heterogeneity for *L-cv*–*L-ku*.	
h_i	distance from the scatter point	
Hmean	mean elevation	m
L-cv	L-moment coefficient of variation	
L-ku	L-moment coefficient of kurtosis	
l_r	sample L-moment of the r order	
L-sk	L-moment coefficient of skewness	
m	month	
MAM(*n*-day)	average of the AM(n-day) time series	m^3/s
MAP	Mean Annual Precipitation	mm
m_{fail}	month with a failure	
m_{tot}	total number of months	
p	percentage	
Q	discharge	m^3/s
Q(7,10)	10-years return period annual minimum 7-day discharge	m^3/s
Q(7,2)	2-years return period annual minimum 7-day discharge	m^3/s
Q(7,2)/A	Q(7,2) normalized by catchment area	$l/s/km^2$
Q50	50 percentile flow index	m^3/s
Q70	70 percentile flow index	m^3/s
Q70/A	Q70 normalized by catchment area	$l/s/km^2$
Q90	90 percentile flow index	m^3/s
Q95	95 percentile flow index	m^3/s

Symbol	Description	Unit
Q99	99 percentile flow index	m^3/s
ri	supply restriction for i state	%
r_j	risk level	
RMSE	Root Mean Square Error	
$\boldsymbol{S}$	covariance matrix	
Sl	mean slope	%
SP	Soil Permeability	%
Su	Designed water supply	
T	temperature	°C
$t_{2(i)}$	values of *L-cv* at site *i*	
$t_{3(i)}$	values of *L-sk* at site *i*	
$t_{4(i)}$	values of *L-ku* at site *i*	
T_f	length of time a system's output remains unsatisfactory after a failure	month
$\boldsymbol{u}$	L-moments coefficients vector	
Vi	threshold volume for i state	
v^m_{dr}	required storage for the month m	m^3
w_i	weight functions assigned to each scatter point	
X-UTM	longitude in Universal Transverse Mercator coordinate system	m
Y-UTM	latitude in Universal Transverse Mercator coordinate system	m
$Z^*(x0)$	local estimate at the unsampled position x_0	
ZF	objective function	
z_i	local estimate at station i	
α	reliability coefficient	
β_i	i-th probability weighted moment	
γ	resiliency coefficient	
ΔH	difference between the maximum and the minimum high	m
θ	general parameter	
λ_r	L-moment of the r order	
ν	vulnerability coefficient	
ρ	lag correlation	
τ_i	coefficient of the i-th L-moment	
$\overline{t_2}$	group mean of *L-cv*	
$\overline{t_3}$	group mean of *L-sk*	
$\overline{t_4}$	group mean of *L-ku*	
$\hat{z}_i$	regional estimate at station i	

CHAPTER 1 INTRODUCTION

1.1 MOTIVATION AND SCOPE OF THE RESEARCH

In an increasingly vulnerable world, nations, communities and common people have to cope daily with suffering and loss of lives and livelihood resulting from disasters due to natural and human-induced hazards (Briceño, 2007).

Globally, the number of disasters has grown over the last decades. Given the projections related to the global climate change, an aggravation of this trend is expected. Drought is one of the major threats to people's life and community socio-economic development. Each year, disasters originating from prolonged drought not only affect tens of millions of people, but also contribute to famine and starvation among millions of people, particularly in some African countries.

Drought tends to occur less frequently than other hazards, as it is shown in Fig. 1.1, which data are taken by the last complete study about droughts by CRED CRUNCH (2006) available on line.

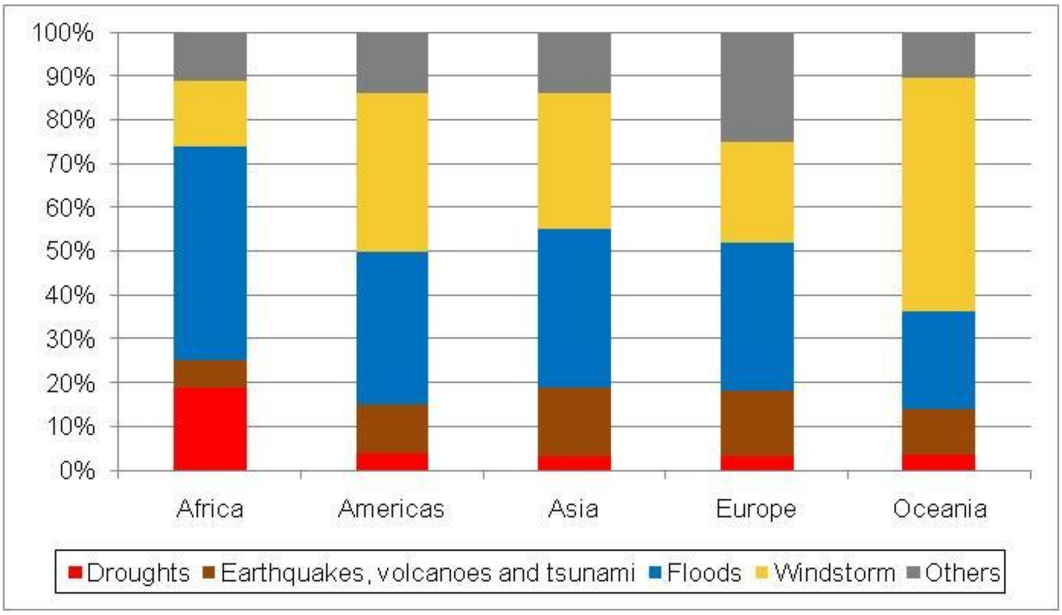


Figure 1.1 Proportion of disaster occurrence by continent: 1970-2006 (CRED CRUNCH, 2006).

However, when it occurs, it generally affects a broad region for seasons or years at a time. The result is that a larger proportion of the population is affected by drought than by other disasters (Fig. 1.2).

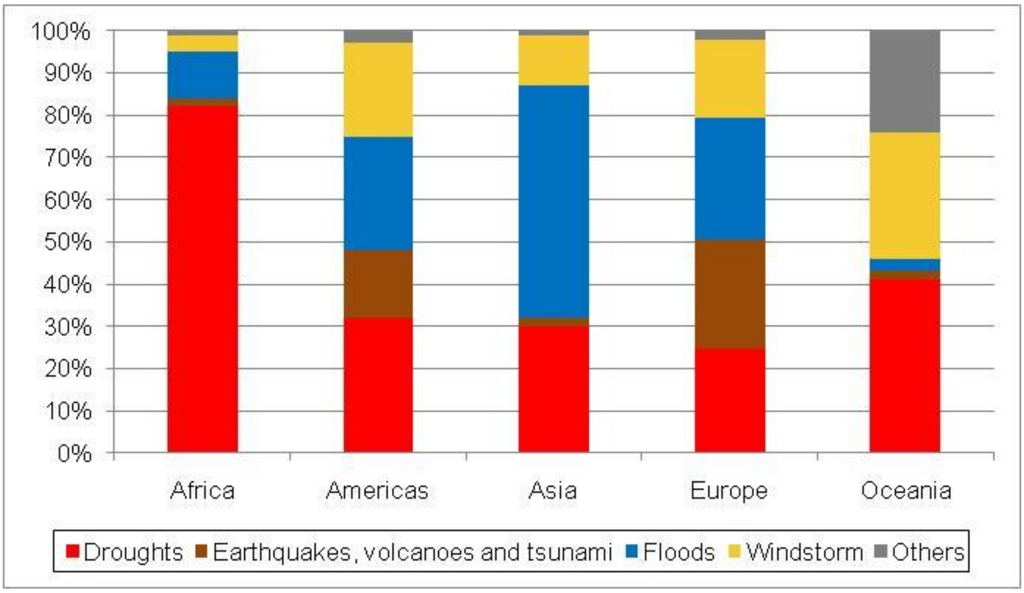


Figure 1.2 Proportion of persons affected by each disaster type per continent: 1970-2006 (CRED CRUNCH, 2006).

Regarding the Africa's situation, Fig. 1.1 and 1.2 show that drought disasters account for less than 20 percent of all disaster occurrences in this continent, but they account for more than 80 percent of all people affected by natural disasters. Some regions are more prone to drought disasters, and each country differs in its capacity to cope with and respond to the effects of drought. For example European countries are able to reduce the impact of drought on life-losing but have huge economic losses, while prolonged drought in Africa can severely damage countries' development, contributing to malnutrition, famine, loss of life, and emigration (Fig. 1.3).

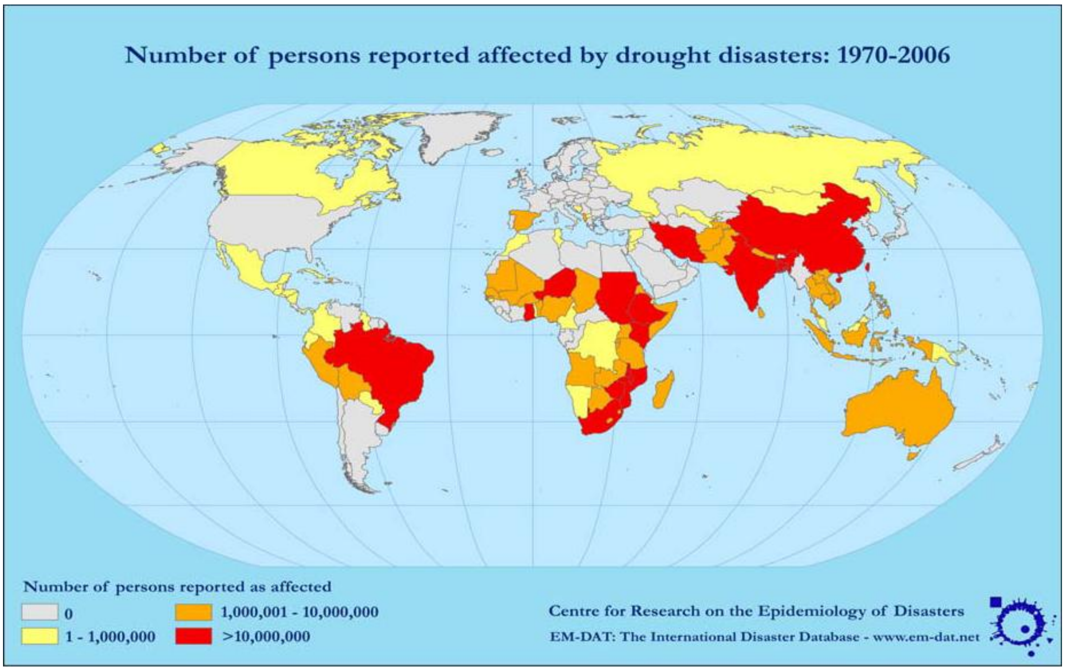


Figure 1.3 Number of person affected by drought disasters 1970 – 2006 (CRED CRUNCH, 2006).

Drought is a natural hazard that evolves over the time, without a crash event. Moreover a rapid response prevent drought from causing famine, but even a major news story. For those reasons droughts are largely unreported by the mass media and their seriousness, their magnitude, their consequences and the importance to prevent from them are unknown to most of the people (Cate, 1994). On the contrary the two worst hazards during the period 1960-2010 are droughts (Fig. 1.4).

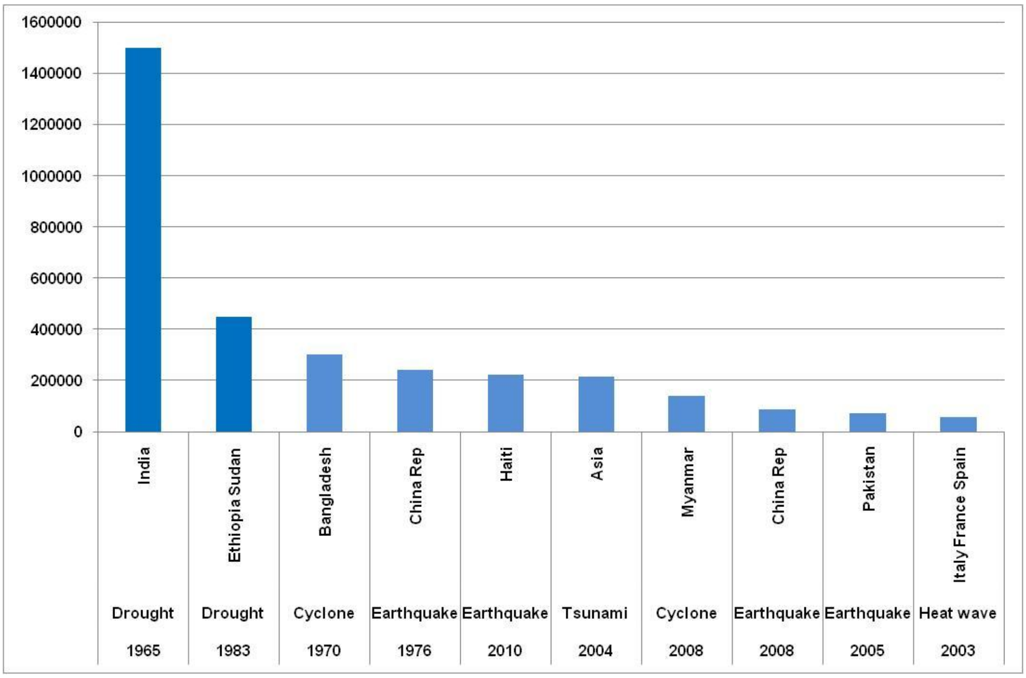


Figure 1.4 Top 10 natural disaster with highest numbers of casualties, 1960-2010 (source: Guha-Sapir et al., 2004; CRED CRUNCH, 2010).

Drought is the most complex and least understood of all natural hazards and at the same time affects more people than all the other natural hazards (Hagman, 1984). Drought is a slow-onset hazard, which provides time to consider and address its complex root causes, such as understanding people's vulnerabilities, and identifying unsafe conditions related to poverty, exposed local economies, livelihoods at risk, lack of strategies and plans. Understanding these issues allows government authorities and the public to undertake effective drought mitigation and preparedness measures.

Given projected increases in temperature and uncertainties regarding the amount, distribution and intensity of precipitation, the frequency, severity and duration of drought may increase in the future (Wilhite, 2008). Even if the discussion about the causes is still open a general agreement exists about the non-stationarity of the climate (Fig. 1.5). For example climate change projections for the Mediterranean region derived from global climate model driven by socio-economic scenarios (Intergovernmental Panel on Climate Change, 2001) result in an increase of temperature (1.5 to 3.6°C in the 2050s) and precipitation decreases in most of the territory (about 10 to 20% decreases, depending on the season in the 2050s). Climate change projections also indicate an increased likelihood of droughts (Kerr, 2005) and variability of precipitation – in time, space, and intensity – that would directly influence water resources availability.

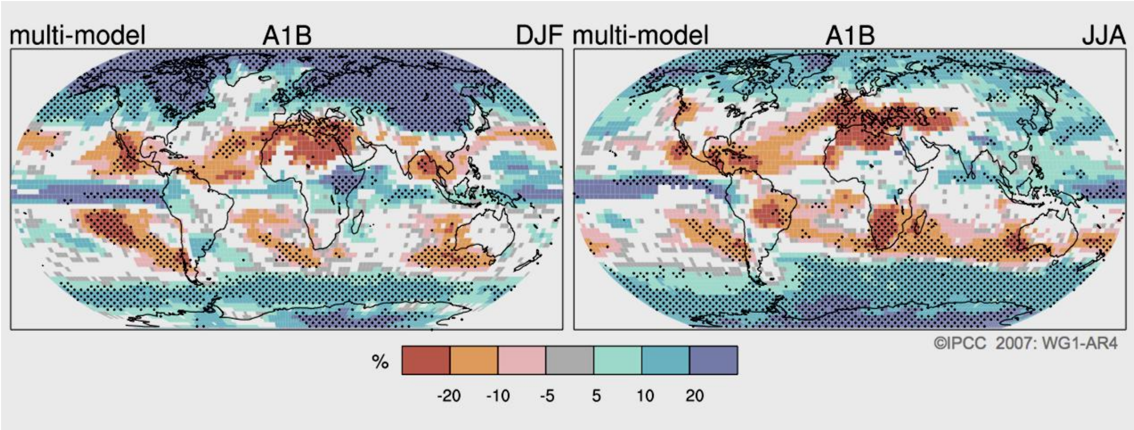


Figure 1.5 Climate future scenarios: relative changes in precipitation (in %) for the period 2090–2099, relative to 1980–1999. December to February (left) and June to August (right) (IPCC, 2007).

In this framework the present dissertation aims to investigate all the parts of the risk management chain.
Regarding the risk identification, it has been studied the evolution of low flow indices. On their basis it is possible to have a complete characterization of the hydrological droughts. In particular with a regional regression approach, the application at ungauged sites, the most common situation in real world, is carried out. The regionalisation regression approach considers the studied territory divided into a given number of homogeneous regions or zones. Low flow indices are determined using data from gauge stations of the region and with some sort of regression between the low flow characteristic of interest and catchment area characteristics that are available for ungauged sites.
Regarding the drought risk the attention is focused on water supply systems and their relation with the entire basin. An original procedure for drought risk assessment is proposed. The probability to have a water shortage in the water supply system is determined in function of the volume stored in the reservoir with Monte Carlo simulations. Threshold values are identified considering the probability to assure a given fraction of the demand in a certain time horizon. A drought mitigation procedure is proposed, associating at every threshold level a demand reduction. The operational rules are defined and procedure is optimized and verified with long term simulations. Values that prevent catastrophic shortages but at the same time do not cause unnecessary restrictions have been defined.

1.2 OVERVIEW

Differently from most of extreme hazards like floods, earthquakes and hurricanes, drought has a slow evolution in time. Its consequences take a significant amount of time with respect to its interception to be perceived by the socioeconomic systems. Taking advantage of this feature, an effective mitigation of the most adverse impacts of drought is possible.

The aim of this dissertation would be the improvement of an innovative procedure for drought risk identification and assessment in order to develop mitigation measures. The present work articulates on the structure described below.
Chapter 2 gives an overview of droughts and problems related to droughts with a special accent on the risk management framework. The dissertation starts with several definitions of droughts, since that numerous definitions of drought continue to be employed. Given these different drought definitions a general one is proposed. Even the different drought typologies are defined and characterized to give an overview of the application on drought risk of the procedure developed within the Graduate College for managing risk due to natural hazards. The three steps constituting the drought risk assessment are described in detail. The European Union legal framework dealing with drought is also presented.
The risk management chain starts with the risk identification. Its first step is to identify the hazard. Identifying the occurrence, the extent and the magnitude of a drought is a delicate task, requiring detection of supplies depletions and demand increases. Drought indices, particularly the meteorological ones, can describe the onset and the persistency of droughts, especially in natural systems. In Chapter 3 the existing indices are described, in particular the hydrological indices derived from streamflow data. Their reliability can be affected by the lack of observed streamflow data, a diffuse problem in the real world. In order to overcome these problems and to estimate low flow statistics in ungauged sites it is possible to refer to a regional statistical analysis, widely used since log time and in different disciplines. It consists in inferring data in ungauged stations using hydrological and statistical methods applied over a more or less wide area, a region. An original method of low flow indices regionalisation is proposed. The study is applied to Tuscany rivers discharges dataset. A heavy work is done to reach a consistent dataset and selected low flow indices are calculated for the considered hydrometric stations. Some instruments present in literature for flood regionalisation are combined in an innovative procedure. L-moments are used to subdivide the area of study into homogeneous sub-regions. Low flow indices at ungauged basins are evaluated in different ways. Inverse Weighted Distance and a geostatistical method, Universal Kriging, are the utilized interpolation techniques. In order to improve the capability of low flow statistics in ungauged sites a multivariate modelling is assessed. For each gauge station catchment area a set of geomorphoclimatic characteristics is determined and for each sub-region a novel relation connecting low flow indices and geomorphoclimatic characteristics is found. The results are validated using the jackknife method. The RMSE – Root Mean Square Error is assessed in order to compare the results, to quantify the accuracy of the different techniques and to define the most suitable procedure for low flow regionalisation.
This procedure is really helpful in real applications because allows determining low flow indices in ungauged river sections, the most common case. Therefore it is a powerful instrument for drought identification.
In Chapter 4 an original procedure for drought risk assessment is proposed. To assess the drought risk the vulnerability of the system has to be taken into account. Shortages

in water supply systems depend not only on the hydro-meteorological situations, but even on water storage, demand fluctuation and actions carried out in order to reduce drought effects. In order to overcome these difficulties, shortages are characterized by means of an index evaluating the performances of the system and analysing the probabilities of shortages. The chosen index is the level in the reservoir. An analysis of the relationship between failure of water supply systems and reservoir volumes for the urban area of Firenze in central Tuscany, in central Italy, is performed. The probability to have definite degree of shortage in the water supply system is evaluated in function of the volume stored in the reservoir at the beginning of the month with Monte Carlo simulations carried out using the software package WEAP. Taking into account the specificity of each system, this procedure can be applied to every water supply systems.

Once that the values of threshold levels are connected with a certain risk of failure it is possible to mitigate drought effects through operational rules. In Chapter 5 a novel optimization of drought mitigation rules is described. A set of measures associated to a drought scenario are activated when the drought indicator reaches a predefined level. The objective of the analysis is to define the thresholds for the declaration of the pre-alert, alert and emergency scenarios. The correct definition of critical thresholds implies to reach a balance between the frequency of declaration of drought scenarios and the effectiveness of the application of measures. If drought scenarios are declared too early, users are frequently exposed to unnecessary restrictions. On the other side if the declaration of drought scenarios is delayed, it may be too late for the measures to be effective. An objective function is proposed to minimize the deviation of each supply from the respective demand targets while the system is operating under drought management rules. The individuated rules are verified with historic and synthetic streamflow series. Performance indices (reliability, resiliency and vulnerability) are calculated to assess the effect of proposed rules.

Finally, Chapter 6 summarises the mean achievements of the research, highlighting the most important points and offering an outlook on future investigation still required in this field.

CHAPTER 2 – DROUGHT RISK

2.1 DEFINITIONS OF DROUGHT

Drought is a natural part of climate, although it may be wrongly considered as a rare and random event. It occurs in all climatic zones, but its characteristics vary significantly from one region to another, affecting heavily only the prone areas. Drought is a temporary anomaly; it differs from aridity, which is a permanent feature of climate with very low annual or seasonal precipitations. Drought is the most complex of all natural hazards: despite the attempts at unification, several definitions of drought continue to be employed (Wilhite et al., 2000).

The World Meteorological Organization (WMO) defines the drought following Hounam et al. (1975) as a temporary and random deviation from average levels of the reference variable [i.e. precipitation].

According to Rossi (2003a) drought is defined as the occasional and recurring situation with a strong reduction compared to the normal values of water availability for a significant period of time and over a wide area.

The UN/ISDR (2007) gives a definition of drought as a deficiency of precipitation over an extended period of time, usually a season or more, which results in a water shortage for some activity, group, or environmental sectors.

Wilhite (2008) defines the drought as a recurrent feature of climate that is characterized by temporary water shortages relative to normal supply, over an extended period of time – a season, a year, or several years, in a wide region.

Perhaps the most general definition is the one which considers drought as a significant decrease of water availability during a long period of time and over a large area. This implies that drought should be considered as a three dimensional event characterized by its severity, duration and affected area.

Drought differs from other natural hazards in a variety of way. Drought is a slow onset natural hazard that is often referred to as a creeping phenomenon. It starts with a deviation of precipitation from normal or expected values. This accumulated precipitation deficit may accumulate quickly over a period of time or it may takes months before the deficiency begin to show up in reduced streamflow, reservoir level, or increased depths to the ground water table.

It is often difficult to know when a drought begins. Likewise it is also difficult to determine when a drought is over and according to what criteria this determination should be made. The end of drought is due to a return to normal precipitation. But a single rainfall event cannot determine the end of drought. Reservoirs and groundwater levels need to return to normal or average conditions. Temperature, wind and relative humidity are also important factors to include in characterizing drought from one location to another. Definitions also need to be application specific because drought impacts will vary between sectors. Drought conjures different meanings for water managers, agricultural producers, hydrologic power plant operators and wildlife biologists.

Drought impacts are non-structural and extend over a larger geographical area than damages that result from other natural hazards such as floods, tropical storms and earthquakes. This, combined with drought's creeping nature, makes it particularly challenging to quantify impacts and even more challenging to provide disaster relief for drought than for other hazards. These characteristics have hindered the development of accurate, reliable and timely estimates of the severity and impacts, such as drought early warning systems and ultimately, the formulation of drought preparedness plans.

2.2 DROUGHT TIPOLOGIES

According to the different component of the hydrologic cycle affected by a drought event, it is possible to give different operational definitions of drought. Operational definitions identify the onset, severity and the end of a drought and refer to the sector, system, or social group impacted by drought (Rossi, 2007). It is possible to distinguish between: meteorological, agricultural, hydrological and socio-economic drought (Fig. 2.1).

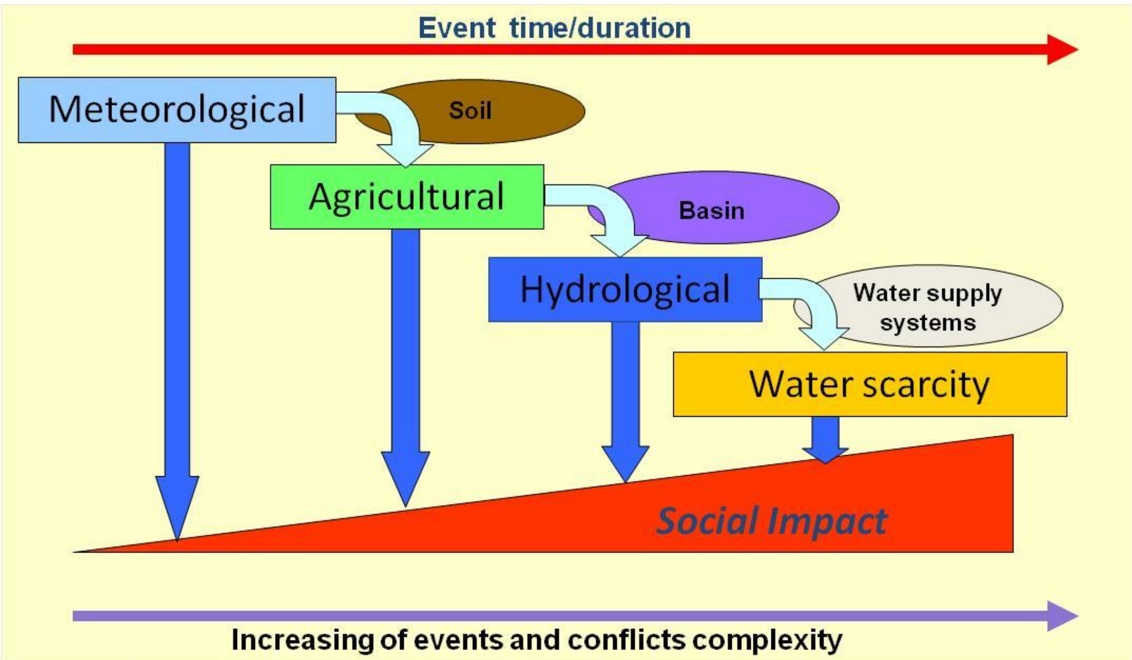


Figure 2.1 Operational drought typologies: interrelations and social impact.

Meteorological drought specifies the degree of deficient precipitation from the threshold indicating normal conditions (e.g. average) over a period of time, and the duration of the period with decreased precipitation. Definitions of meteorological drought are region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. In many cases the primary indicator of water availability is precipitation. It is caused by earth processes: complex geophysical and oceanographic interactions and influenced by interactions with the biosphere and the solar energy fluctuations. In addition to precipitation lower than normal, meteorological drought may also imply high temperatures, high speed winds, low relative humidity, increased evapotranspiration, less cloud cover and great sunshine causing reduced infiltration, less runoff, reduced deep percolation and reduced groundwater recharge (Rossi, 2003a).

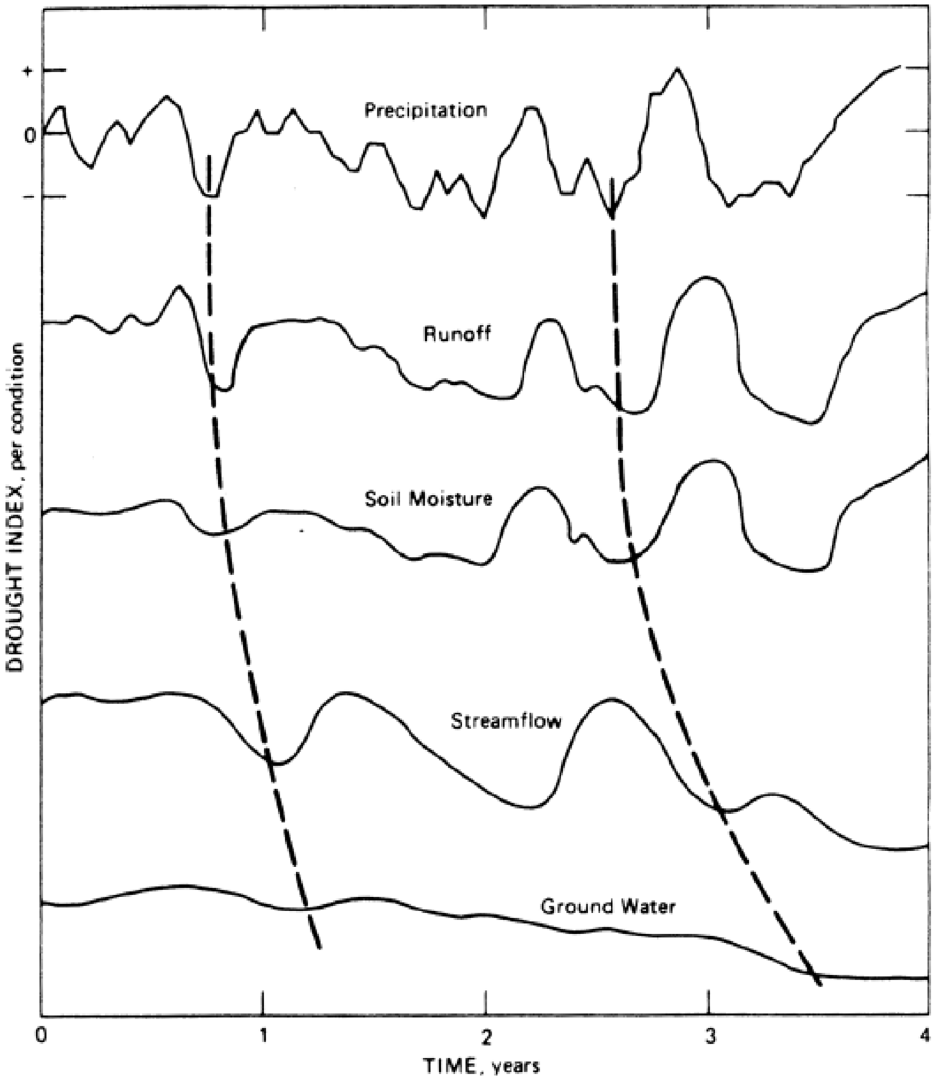


Figure 2.2 Schematic illustration of how hypothetical precipitation deficits and surpluses ideally proceed throughout the hydrological cycle in a delayed and less sharply oscillating way. Different drought typologies are influenced by different hydro-meteorological variables (Rasmusson et al., 1993).

The agricultural drought for rain-fed agriculture is defined as a deficit in soil moisture following a meteorological drought that produces negative impacts on crop production and natural vegetation growth. Its occurrence depends on the entity of the meteorological drought transformed by the water storage effect on soil and vegetation. In particular such water storage causes a delay in the deficit occurrence and modifies its entity in relation to the initial conditions and to the evapo-transpiration process. It is also defined an agricultural drought for irrigated agriculture, even if less utilized for practical applications. It is a water shortage in irrigation districts due to drought in surface or groundwater resources supplying agricultural use.

Hydrological drought is concerned with the consequences of rainfall deficiency in the hydrologic system. It refers to the decline in surface and subsurface water supply. Hydrological droughts are usually out of phase with or lag behind the occurrence of meteorological and agricultural droughts because it takes longer for precipitation deficiencies to show up in components of the hydrological system (Fig. 2.2). It can be measured with threshold levels on rivers stream flow, lakes and groundwater (Vogt and Somma, 2000; APAT, 2006).

The socioeconomic drought occurs when the drought, started as a meteorological, agricultural or hydrological event, has impacts on population and economy. The demand for an economic good exceeds the supply as a result of a weather-related shortfall in water supply (Dracup et al., 1980). Usually it is due to water shortages on water supply systems.

Water shortages refer to the relative shortage of water in a water supply system that may lead to restrictions on consumption. Shortage is the extent to which demand exceeds the available resources and can be caused either by drought or by human actions such as population growth, water misuse and inequitable access to water. In particular a permanent situation of shortage with reference to the water demands in a water supply system or in a large region, characterized by an arid climate or a fast growth of water consumptive demands, is called water scarcity. In addition to water shortages droughts also cause water quality problems, since water quality parameters deteriorate during drought due to lack of dilution and water may not be acceptable for human consumption (Iglesias et al., 2007).

2.3 DROUGHT RISK ASSESSMENT

Drought differs from all of the other natural hazards for several reasons. Drought is a slow-onset natural hazard and it is often difficult to know when a drought begins. Likewise is difficult to determine when a drought is over. Drought impacts are non-structural and spread over larger geographical areas than other natural hazards. Thus it is particularly challenging to quantify a drought risk (Wilhite, 2008).

There are several definitions of drought risk. Following Wilhite (1993) definition, drought risk is a product of exposure to the hazard and social vulnerability. A hazard is a potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. Each hazard is characterized by its location, intensity, frequency and probability. Drought is a natural hazard but it is also a man-affected phenomenon. It is recognized that drought is perceived like a disaster only when it have impacts on people, economy, and environment and their ability to cope with and recover from it. Therefore risk is the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or

environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions (Alecci et al., 2007).
For drought the concept of hazard, according to statistical hydrology, is defined as the probability that a hydrological variable (e.g. Q70) exceeds or goes below a certain threshold at least once in a given number of years. The threshold level may be a constant or it may vary seasonally. Assuming stationarity and independence of the events, the risk can be computed (NDMC, 2006). Similarly, in reliability theory, hazard is defined as the probability of failure for the system under investigation. For drought assessment, vulnerability is the degree of loss to a given element at risk or set of such elements resulting from the occurrence of the natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total loss). A process to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend, is required (UN/ISDR, 2009).

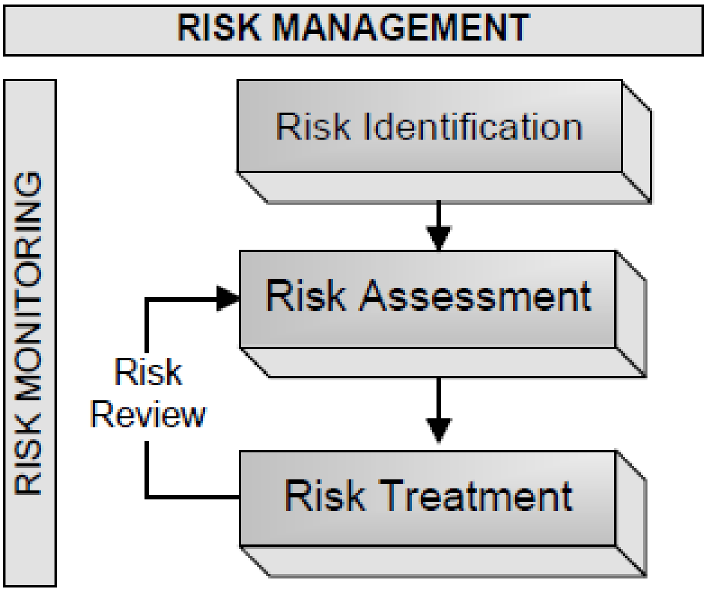


Figure 2.3 The general risk management framework developed within the IGC 802 (Pliefke et al., 2007).

A general procedure to manage risk in any situation or field in which an undesired or unexpected event could be significant is developed within the International Graduate College IGC 802. It provides a greater insight of the possible outcomes and thus it gives the possibility to control the impacts.
As illustrated in Fig. 2.3 the three main components of the framework are the risk identification, the risk assessment and the risk treatment. They are performed sequentially throughout the risk management process even if a risk review step and a continuous risk monitoring are performed in parallel. The risk review process has the role to constantly include all new information, knowledge and experience about the risk and to indicate its evolution within the process over time (Pliefke et al., 2007).

The prerequisite to perform the risk identification phase and therefore to initiate the operation of the risk management chain is the condition of being aware of a dangerous situation. Then the first step is to identify all the sources of events that are able to cause danger to the system functionality (Pliefke et al., 2007). Identifying the occurrence, the extent and the magnitude of a drought that is identifying the hazard, is a delicate task, requiring detection of supplies depletions and demand increases. Drought indices, particularly the meteorological ones, can describe the onset and the persistency of droughts, especially in natural systems (Bonaccorso et al., 2007). Furthermore drought indices have to be used cautiously when applied to water supply systems. They show little correlation with water shortage situations. Such shortages depend also on water storage, demand fluctuation and on the actions carried out in order to reduce drought effects. For that reason in this work a more dynamic indicator relating supply and demand is required in order to identify situations when there is risk of water shortages (Garrote et al., 2008).
Once the model domain is defined and all possible hazards to the system are identified, the risk assessment phase starts. It consists of two sub-procedures, the risk analysis and the risk evaluation module (Pliefke et al., 2007). The drought vulnerability assessment includes two components that define the causes of risk: direct exposure to drought (e.g. location and other natural factors) and social and economic impacts. The UN/ISDR (2007) define vulnerability as "the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards". Vulnerability analysis provides a framework for identifying the social, economic, political, physical, and environmental causes of drought impacts. It focuses on the underlying causes of vulnerability rather than to its result, the negative impacts, which follow triggering events such as drought. In Europe the drought of 2003 affected 19 countries with a total estimated cost that exceeded 11.6 billion Euros (Santos et al., 2010). Recently, there has been debated on the apparent increase, regarding the event frequency and the affected area, of droughts and on the possible physical causes of such circumstance. In the Mediterranean basin, if precipitation decrease pointed out by the climate change models (Bates et al., 2008) is confirmed, the consequences would be severe in terms of the progressive scarcity of surface water due to the high demand for agricultural, industrial, and tourist activities and of the intensification of erosion and desertification processes (New et al., 2002; Vicente-Serrano et al., 2004). The increasing of vulnerability due to climate change is therefore an important factor to be considered in drought risk analysis. Understanding trends in drought-related impacts over time is important for projecting future impacts and understanding changing vulnerabilities.
Each drought produces a unique set of impacts, depending not only on the drought's severity, duration, and spatial extent but also on social conditions. For practical purposes, the drought impacts can be classified as economic, environmental, or social, even though several of the impacts may actually span more than one sector. These impacts are symptoms of underlying vulnerabilities. Therefore, impact assessments are a good starting point to determine underlying vulnerabilities to target response

measures during drought. An impact assessment highlights sectors, populations, or activities that are vulnerable to drought.

Drought impacts assessments begin by identifying direct consequences of drought, such as reduced crop yields, livestock losses, and reservoir depletion. These direct outcomes can then be traced to secondary consequences (often social effects), such as the forced sale of household assets or land, dislocation, or physical and emotional stress (Wilhite, 1991).

In real cases it is quite complicated to define the vulnerability of a complex system in condition of water shortages, due to the difficult to quantify the losses in absence of fresh water (i.e. how to define the vulnerability of a system with 24 hours of no water supply), but even because water supply systems are characterized by a high level of complexity and interactions among the different components (MEDROPLAN, 2006). To overcome these difficulties, traditionally, characterization of the shortages in a water system has been carried out by means of a set of performance indices, trying to describe different aspects such as reliability, resiliency and vulnerability (Hashimoto et al., 1982). Indeed, stochastic nature of inflows, high interconnection between the different components of the system, presence of many conflicting demands varying during time, supply restrictions and uncertainty related to the actual impacts of extreme events, make the risk assessment of a water supply system a problem that is better faced analysing the probabilities of shortages of different entities (Alecci et al., 1986). In the approach used in this work these difficulties are solved analysing the relationship between water crisis and failure of water supply systems and reservoirs volumes, in order to help the policy makers to develop operating rules for drought mitigations.

Once the risk on the system has been analysed and graded into risk classes, the risk treatment phase, the last risk management framework procedure is started (Pliefke et al. 2007). In this work the attention is focused particularly on risk reduction and on mitigation measures.

The goal of drought risk management is to increase the coping with capacity of society, leading to a greater resilience. Mitigation is the set of structural and non-structural measures undertaken to limit the adverse impact of hazards. Mitigation can be defined as any structural or physical measures (e.g. appropriate crops, sand dams, engineering projects) or non-structural measures (e.g. policies, awareness, knowledge development, public commitment, and operating practices) taken to limit the adverse impacts of natural hazards, environmental degradation, and technological hazards.

Before drought occurrence, mitigation actions can be implemented to build resilience into an enterprise or system so that it will be less affected when drought eventually occurs. Some mitigation actions can require relatively small changes in people's lives while others may require the re-evaluation and modification of the basic elements of livelihoods and production systems. An important mitigation measure is the development of drought preparedness and contingency plans that detail specific measures to be taken by individuals or responsible agencies both before and during drought. Preparedness is defined as established policies and specified plans and activities taken before an apparent threat. Its goal is to prepare people, to enhance institutional and coping capacities, to forecast or warn of approaching dangers, and to ensure coordinated and effective response in an emergency situation (UN/ISDR, 2009). Making the transition from crisis to drought risk management is difficult because governments and individuals typically address drought-related issues through a reactive approach and very little institutional capacity exists in most countries for altering this paradigm. Drought mitigation planning is directed at building the institutional capacity necessary to move away from this crisis management paradigm. This change is not expected to occur quickly – it is in fact a gradual process that requires changes in government policies and human behaviour. Drought plan objectives will vary within and between countries and should reflect the unique physical, environmental, socioeconomic, and political characteristics of the region in question (Wilhite, 1991).

Drought mitigation requires the use of all the components of the cycle of disaster management (Fig. 2.3), rather than only the crisis management portion of this cycle. The crisis management is the unplanned reactive approach that implies tactical measures to be implemented in order to meet problems after a disaster has started. On the other side proactive management is given by the strategic measures and the actions planned in advance, which involve modification of infrastructures or existing laws and institutional agreements.

Typically, when a natural hazard event and the resultant disaster has occurred, institutions and stakeholders start the reactions with impact assessment, response, recovery, and reconstruction activities to return the region or locality to a pre-disaster state (Fig. 2.4). Past experience with drought management in most countries has been reactive or oriented toward managing the crisis. Individuals, government, and others consider drought to be a rare and random event. As a result, planning is completed in preparation for the next event. This approach often results in inefficient technical and economic solutions since actions are taken with little time for evaluating optimal actions and stakeholder participation is very limited. Because of this emphasis on crisis management, countries have generally moved from one disaster to another with little, if any, reduction in risk. In addition, in most drought-prone regions, another drought event is likely to occur before the region fully recovers from the previous event. Since drought is a normal part of climate, strategies for reducing its impacts and responding to emergencies should be well defined in advance.

The risk management or proactive approach to drought management is a more effective mitigation tool than the crisis management or reactive approach. Sharply focused contingency plans, prepared in advance, could greatly assist governments or other institutions in the early identification of drought, lessen personal hardship, improve the economic efficiency of resource allocation, and, ultimately, reduce drought-related impacts and the need for government-sponsored assistance programmes. It includes all the measures designed in advance, with appropriate planning tools and stakeholder participation. The proactive approach provides both short term and long term measures and includes monitoring systems for a timely warning of drought conditions. It also includes a contingency plan for emergency situations. It can be considered an approach to manage risk (Wilhite, 2008).

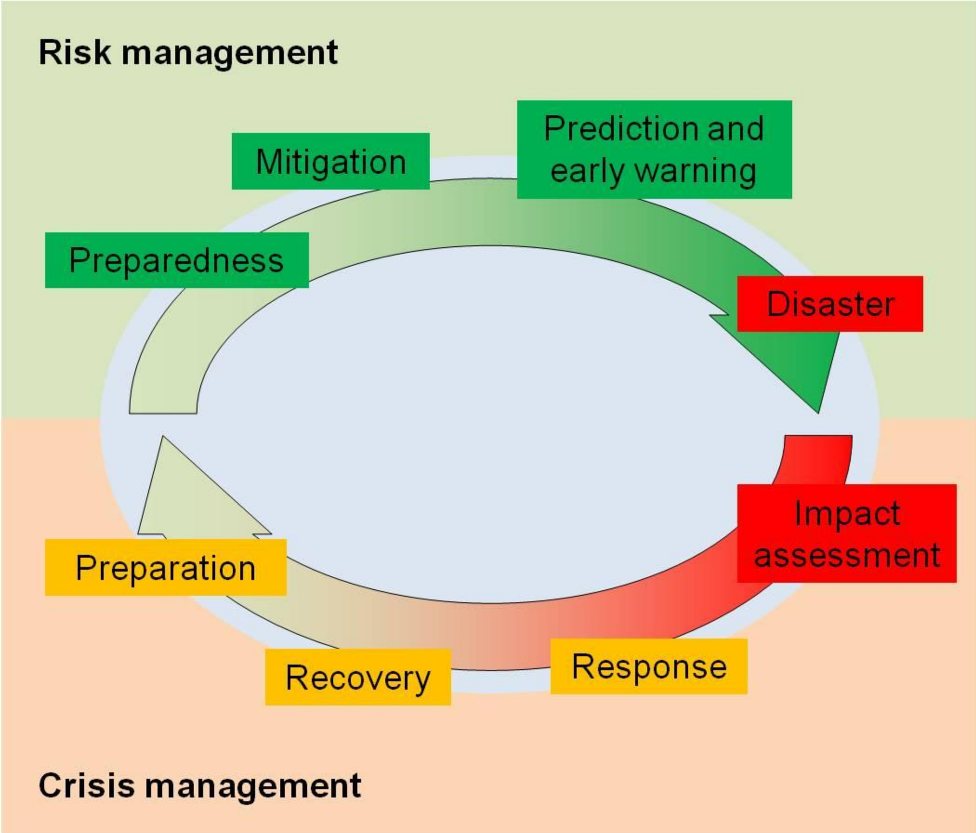


Figure 2.4 The cycle of disaster management.

Drought impacts and losses can be substantially reduced if authorities, individuals, and communities are well prepared, ready to act, and equipped with the knowledge and capacities for effective drought management. It should be recognized that mitigation and preparedness have a greater impact on reducing the scale and effects of drought disasters than ad-hoc emergency response measures. The UN International Strategy for Disaster Reduction (UN/ISDR, 2007) summarizes the elements for a drought risk reduction framework in four main areas of endeavor (Fig. 2.5):

1. Policy and governance as an essential element for drought risk management and political commitment.
2. Drought risk identification, impact assessment, and early warning, which includes hazard monitoring and analysis, vulnerability and capability analysis, assessments of possible impacts, and the development of early warning and communication systems.
3. Drought awareness and knowledge management to create the basis for a culture of drought risk reduction and resilient communities.
4. Effective drought mitigation and preparedness measures to move from policies to practices in order to reduce the potential negative effects of drought.

All of these elements need strong political commitment, community participation, and consideration of local realities and indigenous knowledge. The international and regional communities also play an important role in coordinating activities, transferring knowledge, supporting project implementation, and facilitating effective and affordable practices.

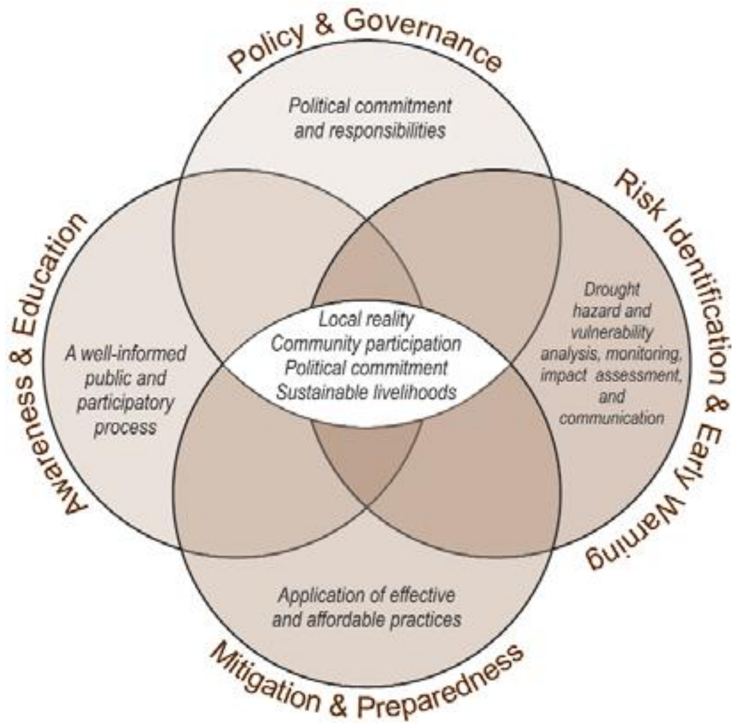


Figure 2.5 Proposed main elements for Drought Risk Reduction Framework (UN/ISDR, 2007).

A starting point for reducing drought risk and promoting a culture of resilience lies in gaining knowledge about hazard occurrence, the potential effects of the hazard, and the related vulnerabilities of potentially affected people and activities. The latter includes the physical, political, social, economic, and environmental vulnerabilities to drought that most societies face and the ways in which hazards and vulnerabilities are changing in the short- and long-term. Understanding the physical nature of the drought hazard and the corresponding impacts and underlying vulnerabilities, and communicating these dangers in an effective manner, forms the basis for developing informed drought mitigation and preparedness measures to reduce the effect of impact of drought while contributing to drought-resilient societies.

2.4 THE EUROPEAN UNION LEGAL FRAMEWORK

The legislation frameworks of the European members countries do not deal with the problem of drought in an individual way: its regulation is usually incorporated in the water legislation, in the civil protection normative or in the legislation related to natural disasters emergency response. This disperse legislation suffers also from three main problems for application and efficiency: the lack of legislative definition of drought concept, the lack of technical indicators for drought declaration and the vague definition of responsibilities of the different institutions (Demmke, 2001).

An attempt to overcome this problem is given by the European Union with a modernized legislation for water resources that include even some references to

drought. Since the 1970s the European Union has maintained a programme for protecting the environment, which entailed the introduction of a policy of sustainable use as one of the current common objectives in the constitutional treaties (article 2 of the Treaty establishing the European Community (TEC)).
In the development of these aims the Union set a new legal framework relating to its policy for water resources through the Water Framework Directive (Directive 2000/60/EC).
The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which:

> *(a) prevents further deterioration and protects and enhances the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems;*
> *(b) promotes sustainable water use based on a long-term protection of available water resources;*
> *(c) aims at enhanced protection and improvement of the aquatic environment, inter alia, through specific measures for the progressive reduction of discharges, emissions and losses of priority substances and the cessation or phasing-out of discharges, emissions and losses of the priority hazardous substances;*
> *(d) ensures the progressive reduction of pollution of groundwater and prevents its further pollution, and*
> *(e) contributes to mitigating the effects of floods and droughts.*
> *(EU Directive 2000/60/EC, art. 1, 2000)*

Focusing on drought and water supply systems management, the Water Framework Directive requires that the responses to all situations of shortage of water resources which have a social cause must be integrated into the Hydraulic Basin Plan and its Programmes of measures and response as a result of which no justification is possible under any circumstance for the short-tem deterioration of the state of the body of water.
Equally the responses to the droughts of natural origin whose intensity and duration may not be exceptional or which it may have been possible to predict with reasonable accuracy, must also be included in the above-mentioned planning. Consequently these droughts also cannot be used to justify the short-term deterioration of the state of bodies of water.
The characterization of situations of exceptional drought, the indicators and appropriate thresholds together with the measures to be adopted for the protection of water resources and ecosystems which may be affected, must be included in the Hydrological Basin Plan and in the programmes of measures and corresponding follow-up.
Only droughts of natural origin and of exceptional character on account of their duration and intensity which, as a result, could not be predicted with reasonable certainty, justify the implementation of a temporary deterioration in the state of the body of water. Anyway the appropriate feasible measures have to be adopted to

prevent the continuing deterioration of the body of water affected or at risk of becoming affected, or where the fulfilment of environmental objectives are at risk.
Each member State of the European Union has to adapt its internal legislature to the Water Framework Directive which requires that hydrological planning regulates the situations of exceptional and non-exceptional drought within its hydrological planning and to have established in a compulsory standard the conditions whereby the exceptional drought may justify a short-term deterioration of the body of water (La Calle, 2008).
Between 1976 and 2006 droughts have dramatically increased in number and intensity in the European Union. The number of areas and people affected by droughts went up by almost 20%. One of the most widespread droughts occurred in 2003 when over 100 million people and a third of the EU territory were affected. The cost of the damage to the European economy was at least € 8.7 billion. The total cost of droughts over the considered period amounts to € 100 billion. The yearly average cost quadrupled over the same period. For that reason in July 2007 the European Commission approved the Communication "Addressing the challenge of water scarcity and droughts in the European Union". This Communication presents an initial set of policy options at European, national and regional levels to address and mitigate the challenge posed by water scarcity and drought within the Union with the final goal of the full implementation of the Water Framework Directive. The following options would be the most appropriate approach for addressing water scarcity and droughts:

- Putting the right price tag on water.
- Allocating water and water-related funding more efficiently.
- Improving drought risk management.
- Considering additional water supply infrastructures.
- Fostering water efficient technologies and practices.
- Fostering the emergence of a water-saving culture in Europe.
- Improve knowledge and data collection.

For each point the issue is presented, some actions at European and national levels are provided, and some good practice are suggested with virtuous examples.
In particular the third point contains some indications on how to overcome drought problems. Drought risk management plans have to be developed in each member state with water stress area mapping, alert levels, and warning systems; an European Drought Observatory and an early warning system on droughts have to be developed at communitarian level. Moreover some economical instruments, the more efficient in the communitarian policies, have to be improved: the use of the EU Solidarity Fund and European Mechanism for Civil Protection will be optimized. In regions where all prevention measures have been implemented according to the water hierarchy (from water saving to water pricing policy and alternative solutions) and taking due account of the cost-benefit dimension, and where demand still exceeds water availability, additional water supply infrastructure can in some circumstances be identified as a possible other way of mitigating the impacts of severe drought. Nevertheless

alternative options like desalination or waste water re-use are increasingly considered as potential solutions (Commission of the European Communities, 2007).

CHAPTER 3 – DROUGTH IDENTIFICATION: REGIONALISATION OF LOW FLOW INDICES

3.1 INTRODUCTION

Due to a slow evolution in time, drought is a phenomenon whose consequences take a significant amount of time with respect to its interception to be perceived by the socioeconomic systems. Taking advantage of this feature, an effective mitigation of the most adverse impacts of drought is possible, more than in the case of other extreme hazards like floods, earthquakes and hurricanes. For a proper characterization of drought phenomena and especially to prepare drought bulletins, it is necessary to undertake studies about weather and climate variables and the systematic monitoring of these parameters. The monitored variables depend on the type of investigation. If the analyse refers to the causes of drought or to meteorological drought the main variable is precipitation. If the analyse refers to the drought effects even other variables that are involved in the water balance should be considered, such as: evapotranspiration, soil water content, surface runoff, water stored in reservoirs and in underground aquifers.

A proper distribution of the monitoring stations network allows identifying the spatial distribution and the temporal evolution of the variables involved in the study of drought phenomena. A monitoring network has the main goal of correctly determining the space-time variability of the quantities of interest. It is therefore necessary that it has long and reliable time series and a good geographical distribution, considering even the elevations distribution, in order to be representative of the entire area under study. Optimal distributions avoid the presence of areas without gauge stations as well as areas with a surplus of stations that would provide redundant information (APAT, 2006).

Drought characteristics (e.g. duration, severity) are difficult to forecast and both time and space variability of drought are not usually well monitored. An effective drought monitoring system, able to provide a timely warning about the possible onset of a drought event, as well as to describe its evolution in time and space is necessary to adequately mitigate droughts impacts. Moreover an accurate selection of methods and tools for drought identification and characterization to be implemented within the drought monitoring system is required (Rossi, 2003b).

Rossi et al. (1992) recommend that a comprehensive approach for studying drought problems have to include, among others, the following topics:

- identification of meteorological causes and drought forecast;
- evaluation of hydrologic drought characteristics at a site and over a region;
- analysis of economic, environmental and social effects of drought.

For all of these characterizations a monitoring system allowing for drought risk evaluating on its multiple aspects is necessary. Meteorological drought is evaluated mainly through a statistical analysis of rainfall precipitation. Several indices are

proposed in last decades with different time resolution and calculation complexity. Agricultural drought and water stresses on plants, trees and cultivations are assessed trough synthetic indices that evaluate indirectly the soil moisture or through satellite remote sensing able to estimate surface soil water content, plants water content, and vegetation coverage.
Hydrological drought is assessed mainly through the analysis of stream-flows time series, considering especially low flow characteristics, and lakes, reservoirs and aquifers levels.

3.2 DROUGHT INDICES

Various methodologies have been proposed for identification, quantification and monitoring of drought phenomena. Among them, the most popular are single factors known as drought indices. They are special combinations of indicators comprising meteorological, hydrological and other types of data. Starting from the 60's several indices and methods were developed to identify and monitor drought events with reference to different drought definitions (Rossi, 2003b).
Drought indices are important and useful elements for drought monitoring and assessment since they simplify complex interrelationships between many climate and climate related parameters. Indices make easier to communicate information about climate anomalies to varied user audiences and allow scientists to assess quantitatively climate anomalies in terms of their intensity, duration, spatial extent and frequency. This allows the analysis of the historical droughts events and their recurrence probability.
Drought indices are employed to characterize drought and its statistical properties. They provide spatial and temporal representations of historical droughts and therefore place current conditions in historical perspective. They are valuable for providing decision makers with a measurement of the abnormality of recent weather for a region. Very important aspects, when drought indices are used, are the thresholds representing the levels of drought severity. Unfortunately, these thresholds cannot be the same for all the basins, since they are depending on the location and on the system that is analysed (Tsakiris and Pangalou, 2008).
A drought index should have the following characteristics to be a good indicator:

- to synthesize a set of information in a single parameter;
- to be easyly interpreted and communicated even to non-experts, but not to be over simplified, losing the essential features for the phenomenon understanding (i.e. the average value of a variable that has a significant spatial variability);
- to allow the assessment of the current situation severity with reference to a series that is stationary in time;
- to be normalized, if possible, to allow comparison between different areas;
- to be formulated, if possible, in probabilistic terms in order to facilitate the hazard comprehension.

Drought indicators are defined as a single observation or combinations of observations that contribute to identify the occurrence, the continuation and the magnitude of a drought event (Hisdal and Tallaksen, 2000). Drought indicators can include measures of streamflow, precipitation, reservoir storage, or the evaluation of meteorological indices function of precipitation, temperature, available water content of the soil, and other variables. The effectiveness of drought indicators depends on the specific region and on the characteristics of the system. No single indicator can work for all regions (Tallaksen et al., 2004).

The fact that they originate from a deficiency of precipitation that results in water shortage for some activity or for some group is common to all types of drought (Wilhite and Glantz, 1985). Rainfall was the first variable to have reliable observations. They became available about two centuries ago and as a result practically all drought indices and drought definitions included this variable either singly or in combination with other meteorological elements.

The beginning and the persistency of droughts can be recognized with meteorological indices. Meteorological indices respond to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by these indices ends without taking into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts. Meteorological drought indices do not take into account human impacts on the water balance, such as irrigation. On the other side hydrological drought indices are based largely on streamflow, as this variable summarizes and is the by-product of essentially each hydro-meteorological process taking place in watersheds and river basins. Hydrological droughts indices may take into account even water management, lake and reservoir levels, and other longer-term hydrologic impacts (Heim, 2002). Drought indicators include mainly meteorological and hydrological drought indices.

Drought indices assess drought conditions in a specific time. However, it is necessary to define a drought threshold value for each one of the drought indices. This threshold distinguishes a drought category and determines when drought responses should begin and end. Tab. 3.1 summarizes the most commonly used drought indices.

The data required for drought assessment are usually daily or monthly data. No smaller time step has significant effect when drought is assessed by general indices. Only in some very specialized indices related to crucial water deficit aspects, a smaller time step can be used. Therefore, for the purpose of establishing drought-meteorological networks, monthly or daily values of the key meteorological or hydrological parameters are required.

Regarding the reference period of drought assessment it seems logical to consider longer periods of time. Furthermore, lag time in hydrological processes makes any kind of drought assessment unreliable if a short period of time is adopted. Based on these thoughts, the task of assessing droughts using general indices can be more efficiently implemented if the reference period is an entire season or an entire year. For the Mediterranean countries the hydrological year starts the first day of October and ends at the end of September of the following year (Svoboda, 2000).

Table 3.1 Summary of the main drought indices with their description and main strengths and weaknesses.

Index	Description and use	Strengths	Weaknesses
Percentage of normal precipitation	Simple calculation; used by general audiences	Effective for comparing a single region or season	Precipitation does not have a normal distribution. Values depend on location and season
Munger Index Munger (1916)	Simple calculation	Effective for meteor. drought	Precipitation is the only parameter used
Deciles Gibbs and Maher (1967)	Simple calculation grouping precipitation into deciles	Accurate statistical measurement Simple calculation Provides uniformity in classifications	Accurate calculations require a long climatic data record
Rainfall Anomaly Index		Sensitive to extreme values	Precipitation is the only parameter used
Standardized Precipitation Index (SPI) McKee et al. (1993)	Based on the probability of precipitation for any time scale, used by many drought planners	Computed for different time scales, provides early warning of drought and helps assess drought severity	Values based on preliminary data may change; precipitation is the only parameter used
Crop Moisture Index (CMI) Palmer (1968)	Derivative of the PDSI. Reflects moisture supply in the short term	Identifies potential agricultural droughts	It is not a good long-term drought monitoring tool
Palmer Drought Severity Index (PDSI) Palmer (1965) Alley (1984)	Soil moisture algorithm calibrated for relatively homogeneous regions Used in the USA to trigger drought relief programmes and contingency plans	The first comprehensive drought index, used widely Very effective for agricultural drought since it includes soil moisture	May lag emerging droughts. Unsuited for mountainous areas of frequent climatic extremes. Categories not necessarily consistent, spatially or temporally. Complex
Palmer Hydrological Drought Index (PHDI) Palmer (1965)	Similar to PDSI but more exigent to consider a drought end. The drought terminates only when the ratio of moisture received/moisture required is 1	Very effective for agricultural drought since it includes soil moisture	Complex. Categories not necessarily consistent, in terms of probability of occurrence, spatially or temporally

continued

Index	Description and use	Strengths	Weaknesses
Reconnaissance Drought Index (RDI) Tsakiris (2004)	Similar to SPI. Basic variables precipitation and potential evapotranspiration	Based on both precipitation and potential evapotranspiration. Appropriate for climate change scenarios	Data needed for calculation of PET
Surface Water Supply Index (SWSI) Shafer and Dezman (1982)	Developed form the Palmer Index to take into account the mountain snowpack	Simple calculation. It includes surface water supply conditions. Combines hydrological and climatic features. Considers reservoir storage.	Management dependent and unique to each basin, which limits inter-basin comparisons. Does not represent well extreme events
Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973)	Calculated with remote sensing data	Allow the comparison between different months/years	Possible underestimation in areas with compact vegetation
Vegetation Condition Index (VCI) Kogan (1995)	Derived from NDVI. Evaluates the vegetation wellness	Useful means for detecting drought onset; it can provide near real-time data	Strongly correlated with agricultural production
Temperature Index (TCI) Kogan (1995)	Calculated with remote sensing data based on brightness temperature	Useful for the evaluation of agricultural and hydrological drought	Consider temperature not moisture. To be integrated with other indices

3.2.1 Examples of meteorological indices: Deciles and Standard Precipitation Index

Two meteorological indices used vary commonly, the Deciles and the SPI, Standard Precipitation Index, are presented as examples of evaluation and classification of drought conditions.

A simple meteorological index is the rainfall Deciles. For the calculation of this index the total precipitation for the preceding three months is ranked against climatologic records.

If the sum falls within the lowest decile of the historical distribution of 3 months precipitation, then the region is considered to be under drought conditions (Kininmonth et al., 2000). The drought ends when the precipitation measured during the previous month lays in or above the fourth decile or the total precipitation for the previous three months is in or above the eighth decile.

The first decile is the precipitation amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. The subdivision into deciles continues until the rainfall amount identified by the tenth decile. It is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications that are presented in Tab. 3.2 (Gibbs and Maher, 1967).

Table 3.2 Classification of drought conditions according to deciles (Gibbs and Maher, 1967).

Decile	Classification
deciles 1-2: lowest 20%	much below normal
deciles 3-4: next lowest 20%	below normal
deciles 5-6: middle 20%	normal
deciles 7-8: next highest 20%	above normal
deciles 9-10: highest 20%	much above normal

The advantage of the decile approach is its computational easiness. On the other side its simplicity can lead to conceptual difficulties. For example, it is reasonable for a drought to terminate when observed rainfall is close to or above normal conditions. But minor amounts of precipitation during periods in which little or no precipitation usually falls, can determine a drought end, even though the amount of precipitation is negligible and does not terminate the water deficit.

The Standardized Precipitation Index (SPI) was developed for the purpose of defining and monitoring drought (McKee et al., 1993). Among the several proposed indices for drought monitoring, the SPI has found widespread application (Heim, 2000; Cancelliere et al., 2007). Guttman (1998) and Hayes et al. (1999) compared SPI with Palmer Drought Severity Index (PDSI) and concluded that the SPI has advantages of statistical consistency, and the ability to describe both short-term and long-term drought impacts through the different time scales of precipitation anomalies. The SPI calculation for any location is based on a series of accumulated precipitation for a fixed time scale of interest (i.e. 1, 3, 6, 9, 12,… months). Such a series is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be compared. The SPI values are subdivided into 8 classifications presented in Tab. 3.3.

Table 3.3 Classification of drought conditions according to SPI values and corresponding event probabilities (McKee et al., 1993)

SPI value	Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Severely wet	4.4
1.00 to 1.49	Moderately wet	9.2
0 to 0.99	Mildly wet	34.1
0 to -0.99	Mild drought	34.1
-1.00 to -1.49	Moderate drought	9.2
-1.50 to -1.99	Severe drought	4.4
-2.00 or less	Extreme drought	2.3

Being a standardized index, the SPI is particularly suited to compare drought conditions among different time periods and regions with different climatic conditions. In Fig. 3.1 is present a graphical representation of the values of the 12-months SPI in United States through the end of December 2010.

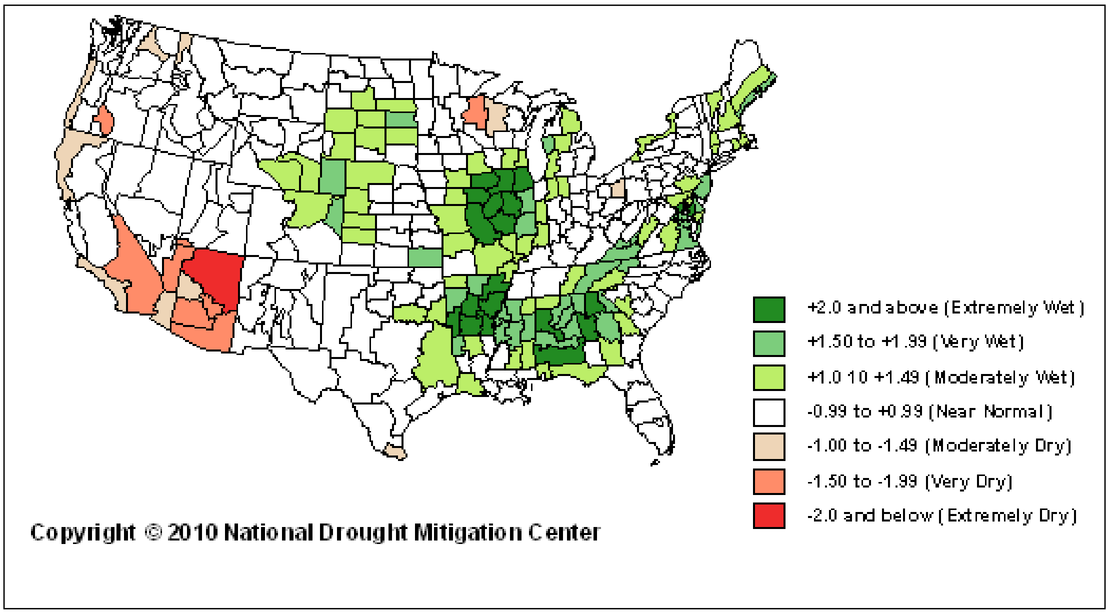


Figure 3.1 12-months SPI in United States through the end of December 2010 (National Drought mitigation centre website: http://www.drought.unl.edu/monitor – December 2011)

3.3 LOW FLOW INDICES

A hydrological drought is a period during which the discharge is below normal or, in a demand orientated study, a period during which the discharge is insufficient. In both cases droughts are characterized through low flow values and a clear differentiation between droughts and low flow periods has to be made.

The term 'low flow period' usually refers to the regime of a stream, which represents the average annual cycle of the streamflow, and the terms 'low flow period' and 'high flow period' are used to describe the normal annual fluctuations of streamflow linked to the annual cycle of the regional climate. Depending on the climate the regime of a stream can show one or more low flow and high flow periods. The equatorial climate for example is marked by two rainy and two dry seasons and streamflow regimes have two corresponding high flow and low flow periods (McMahon and Diaz Arenas, 1982), while a monsoon climate causes only one low flow and one high flow period during the year.

On the other hand droughts are not seasonal characteristics of a streamflow regime. Instead, they are prolonged periods with unusually low streamflow, which does not occur each year. For example in a Mediterranean region the summer months June till October could be the low flow period of a stream, but only in dry and hot summers the stream would experience droughts. Often a period of unusually low streamflow has to last a defined minimal period of time to be considered a drought. Depending on catchment area climate, only the periods with discharge below normal compared to the low flow part of the regime are considered droughts, whereas deviations from the high flow part are rather called streamflow deficiency (Hisdal, 2002). Droughts include low-flow periods, but a continuous seasonal low-flow event does not necessarily constitute a drought. This is usually the case for a catchment in a temperate climate region, where a streamflow deficiency compared to the high flow part of the regime usually have no severe consequences. In a semi-arid region a drought study might therefore also be focused on the high flow season and streamflow deficiencies in the high flow season can either be considered as droughts themselves or as the cause of a subsequent drought during the dry season (Tallaksen et al., 1997).

Low flows are normally derived from groundwater discharge or surface discharge from lakes, marshes, or melting glaciers. Lowest annual flow usually occurs in the same season each year. The natural factors which influence the various aspects of the low-flow regime of the river include the distribution and infiltration characteristics of the soils, the hydraulic characteristics and extent of the aquifers, the rate, frequency and amount of recharge, the evapotranspiration rates from the basin, the distribution of vegetation types, topography and climate. Natural low flows are affected by various anthropogenic impacts which normally include: groundwater abstraction within the sub-surface drainage area, artificial drainage of valley bottom soils for agricultural or building construction purposes, changes to the vegetation regime in the whole catchment or parts thereof trough clearing or planting, modification of land use over large parts of a catchment and direct abstractions or effluent flows into the river channels (Smakhtin, 2001).

Low flows in Europe generally occur during the summer or early autumn (Marsh et al., 2000). Streams draining catchments with permeable soils, where flows are sustained by gradual release of water from storage, usually show a single annual recession with minimum flows occurring in autumn. In contrast, impermeable catchments having little storage capacity may experience more extreme low flows (annual minima tend to be lower, as a percentage of the mean flow) that are often interspersed with episodes of higher flow in response to rainfall events. Furthermore, whilst few rivers in the EU countries are truly ephemeral, the failure of springs or shrinkage of headwater systems can result in the cessation of flows (Zaidmann et al., 2003).

Knowledge of low flow events frequency is required to plan water supply and irrigation systems and moreover to maintain amount and quality of water for wildlife. An appreciation of the frequency at which low flow events of different severity might occur is therefore essential for effective water resource planning. Low flow regime is tightly dependent on the catchment hydrogeological feature and a detailed surface and groundwater catchment analysis is necessary for an accurate characterization. However on a practical perspective, although scientifically proven, statistical analysis is widely applied to derive indices to characterize low flow regimes and as a measure for environmental minimum flow. Low flow frequency behaviour is typically characterized using a stochastic approach based on quantifying the likelihood that flows will persist below a particular level for a certain number of days (Gustard et al., 1992; Tasker, 1987) thus avoiding the need to address all the complicated day-to-day variations in the flow record.

As the majority of flow records are normally insufficient for reliable frequency quantification of extreme low flows events, different types of theoretical distribution functions are used to infer the behaviour beyond the limits of observed probabilities and to improve the accuracy of low flow estimation. The "true" probability distributions of low flows are unknown and till now there is not a general agreement about the distribution that could fit the low flows data. A practical problem is to identify a reasonable functional distribution and to quantify its parameters. A number of different distribution types may all fit the observed annual minima reasonably well and it may not be possible to discriminate between them on an objective basis. In this case a particular model may be favoured for practical reasons, such as computational convenience, or because it exhibits certain characteristics that the user believes a low flow distribution should have. For example, a distribution having a finite lower limit equal to zero (to represent the possibility of recording a zero, but not a negative, flow) is often considered preferable to one that does not. The distribution used for extremes values are evaluated in several studies, but none of them is able to fit the behaviour of rivers in different areas. In Zaidmann et al. (2003) four specific distribution families are identified as the most appropriate to be used:

- Generalised Extreme Value family (GEV);
- Generalised Logistic family (GL);
- Pearson Type-3 family (PE3);
- Generalised Pareto family (GP).

The frequency analysis approach is not able to provide information about the length of continuous periods below a particular flow value of interest. Moreover the described method is not able to give indications of possible deficits of flow. Different methods are used to analyse low flow regimes: a variety of measures and indices are presented in literature. The term "low flow measure" refers to different methods that have been developed for analysing the low flow regime of a river. The term "low flow index" is used predominantly to define particular values obtained from any low flow measure. Low flows characteristics are the basis for hydrological drought studies (Hisdal et al., 2004). With indices derived from low flow it is possible to recognize hydrological droughts that affect mainly water supply systems (Cancelliere et al., 1998; Garrote et al., 2009). Different methods to derive hydrological drought characteristics are needed in order to describe the different ways in which droughts emerge in different areas. The selection of an appropriate method can be even more difficult when drought events of several streams within one region are to be analysed (Menedez, 1995; Tallaksen et al., 1997).

Low flow characteristics are estimated from observed streamflow data, identifying duration curves, indices and percentiles characteristics. Although various low-flow indices describe different aspects of low-flow regime of a river, most of them are obviously strongly intercorrelated. Two main groups of low flow indices are usually used in drought identification. The first group is derived from the Flow Duration

Curve (FDC). The second one is composed by the minimum n-day average discharge indices. These groups of indices are presented in details in the following paragraphs (Pyrce, 2004).

3.3.1 Percentile indices from the flow duration curve

The flow duration curve (FDC) is one of the most informative methods of displaying the complete range of river discharges from low flows to flood events. It is a relationship between all the observed discharge values and the percentage of time that these discharges are exceeded. In other words it is the relationship between magnitude and frequency of streamflow discharges (Castellarin et al., 2004). Following the first definition, it plots the discharges above their exceedance frequency (Fig. 3.2). In other studies the exceedance frequency is frequently defined as the "percentage of time a value is equalled or exceeded" rather than "it is exceeded". This definition has for example been used by Vogel and Fennessey (1994) or Zelenhasić and Salvai (1987). FDC illustrates the frequency distribution of flows in a stream with no regard to their sequence of occurrence.

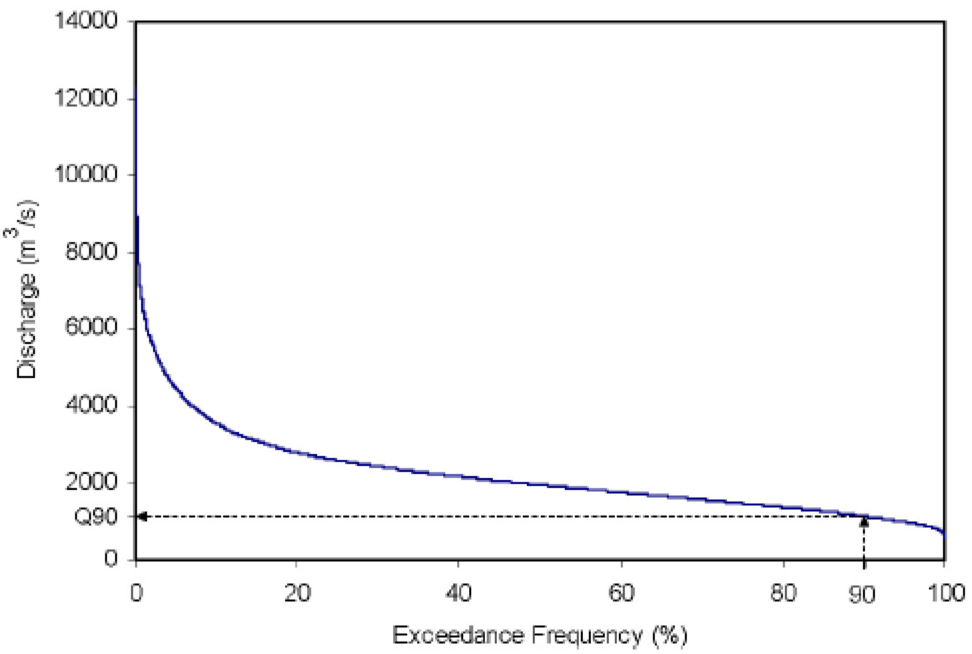


Figure 3.2 Example of flow duration curve: FDC of the River Rhine at Lobith, the Netherlands, 1901-2003 (elaborated with data from http://www.eu-watch.org – December 2011).

The earliest use of FDC is attributed to Clemens Herschel and dates back to 1880 (Forster, 1934). FDCs are still widely used by hydrologists around the world in numerous water related applications like hydropower generation and planning and design of irrigation systems (Forster, 1934; Searcy, 1959), management of stream-pollution, river and reservoir sedimentation and fluvial erosion (Cordova and Gonzalez, 1997; Richards, 1982; Wolman and Miller, 1960). Vogel and Fennessey (1994) present a comprehensive review of FDC applications in water resources planning and

management, while Castellarin et al. (2007) present a comprehensive characterization of FDC regionalisation methods.
A discharge value which is exceeded in a percentage of the time *x* is the *x*-percentile of the FDC, identified with *Qx*. The FDC describes the discharge variability of a stream and allows an easy visual comparison of discharge variability of different streams when several standardised FDCs are plotted together in one graph. A common way of standardising the FDC is to divide the discharge values by the value which is exceeded in 50% of the time, *Q50*. Another way is to divide them by the value of the catchment area of the gauge station (Fleig et al., 2006).
Low flow indices derived from the FDC are the percentiles which indicate a high frequency of exceedance and therefore present the low flow period of a regime. They can be used as a low flow index once they are normalized (Castellarin et al., 2007). Common percentiles used as low flow indices are the 95-, 90- and 70-percentile, *Q*95, *Q*90, and *Q*70 respectively. They are also frequently chosen as values for the threshold levels in drought event definitions.
The FDC can be calculated through data with any kind of time resolution (even if the daily data are usually utilized) and for any record length. Most commonly the whole period of record is used. The FDC is calculated by assigning to each discharge value its rank, *i* in descending order, which means that the largest value gets rank 1, and then the values are plotted over *p*, which is the percentage of data exceeding a value.

$$p = \frac{i}{N} \tag{3.1}$$

Where *N* is the total number of values. To the percentile *Qx* is assigned the discharge value *Q* with the smallest p which is equal or greater than *x*.

$$Qx = Q(\min(p \geq x)) \tag{3.2}$$

Instead of using all the data, a FDC can also be calculated for example for a specific season by taking only all the summer or the winter values of the time series, calculating a FDCS or FDCW respectively.

3.3.2 Minimum n-days average discharge indices

The annual minimum *n*-day discharge, *AM*(*n*-day) is the smallest average discharge of *n* consecutive days within one year. Common averaging interval, i.e. values of *n*, are 1, 7, 10, and 30 days Gustard et al., 1992). An *AM*(*n*-day) can easily be calculated by applying a moving-average filter of *n* days on a daily discharge series and subsequently selecting the minimum of the filtered series. Calculating *AM*(*n*-day)s for several years, the obtained *AM*(*n*-day) time series is the basis for a frequently used low flow index, the mean annual minimum *n*-day discharge, *MAM*(*n-day*), which is the average of the *AM*(*n*-day) time series. In contrast to percentiles from the FDC the *MAM(n*-day) implies a duration aspect, included in the averaging interval; the common notation for a definite *MAM(n*-day*)* is *Q*(*n*-day, return period). In the United States, the most widely used low flow index is the 10-year annual minimum 7-day discharge Q(7,10), which is the *AM*(7-day) with a return period of 10 years (Hisdal et al., 2004). To obtain this value a frequency analysis is carried out on the *AM*(7-day) time series and the value that is observed on average every 10 years is chosen (Fleig et al., 2006).

3.3.3 Selected low flow indices

The choice of the low flow indices to be used in the present work is suggested by various factors. The choice is not obvious and there is not a common choice in literature. It is due to variable user requirements, limitations of existing streamflow database, research objectives, and to the extreme spatial variability of river low-flow regimes. The engineering or water resources planning traditions of a particular country play an important role. Three indices belonging to the groups described in the previous paragraphs are chosen: the Q90, the Q70 and the Q(7,2). These flow indices are frequently selected to evaluate threshold levels in drought event definition. Since the Q90 presents zero value for some years in several gauge stations, in the subdivision into homogeneous regions only the Q70 and Q(7,2) are used.
Q90 and Q70 are common percentiles used as low flow indices. They are respectively the 90- and 70-percentile. Smakhtin (2001) indicated that the "design" low flow range of a flow duration curve is the 70%-99% range, or the Q70 to Q99 range. The Q70 and Q90 flows are often used as low flow indices in the government literature and academic sources. They are also frequently chosen as a value for the threshold level in drought event definition (Pyrce, 2004), as a value that provides stable and average flow conditions (Caissie and El-Jabi , 1995), as a value that gives minimum flow for aquatic habitat (Yulianti and Burn, 1998), and as a threshold for warning water managers of critical streamflow levels (Rivera-Ramirez et al., 2002).
The Q(7,10) and Q(7,2) flows are the most commonly used single flow index (Smakhtin, 2001). By the early 1970's, U.S. agencies which regulated stream pollution based their stream water quality standards on the 7-day 10-year low flow condition (Singh and Stall, 1974). The water quality of any stream was considered to be acceptable unless the streamflow was below the 7-day, 10-year low flow Q(7,10); any diversion made beyond the Q(7,10) could degrade the water quality of the stream beyond the accepted standard (Chiang and Johnson, 1976). The Authority of Arno river basin referred to the 2-year annual minimum 7-day discharge to define low flow. In fact the Q(7,2) is one of the discharge values that are evaluated as indicators for the minimum environmental flow requirement (*Deflusso minimo vitale* - DMV) (AdB Arno, 2001). The annual 7-day low flow (Q(7,1); or MAM7, the mean annual 7-day average minimum flow) is used as an alternative index in the United Kingdom for water abstraction licensing (Smakhtin and Toulouse, 1998).

3.4 LOW FLOW REGIONALISATION

Low flow indices can be easily evaluated at gauged sites from observed streamflow time series, but their reliability can be affected by poor and not accurate streamflow data. Sivapalan (2003) indicated that the prediction of surface water flows in ungauged basins is an urgent problem, of immediate relevance to society, dealing with questions such as the impacts of land use and climatic change, biodiversity and sustainable development. There have been numerous attempts to predict low flows using empirical equations in the United States based on catchment area (main channel length, basin perimeter, drainage area, mean elevation, mean basin slope), channel (channel slope) and meteo-climatic characteristics (precipitation index, average basin precipitation in winter, mean latitude). Other attempts (Vogel and Kroll, 1992) relate the low flow characteristics to the ones of the catchment area aquifers.

Another approach to estimate low flow statistics in ungauged sites is the regional statistical analysis, widely used since long time and in different disciplines. It is the most widely used technique in flow estimation in ungauged sites or where few data are available (Riggs, 1973). Moreover, there is a large consensus that regional frequency analysis yields much more reliable flood quantile estimators than the at-site approach (local frequency analysis) when only short records are available (Durrans and Tomic, 1996).

Regionalisation of streamflow characteristics is based on the premise that catchments with similar geology, topography, climate, vegetation, and soils would have similar streamflow responses. It consists of the identification of regional laws, applicable over a more or less wide area, a region, which generally use catchment characteristics as independent variables (Santhi et al., 2008).

Regionalisation techniques can be used to infer the long term flow characteristics for sites where short or no records are available. The flow characteristics for the site of interest are found basing on stream flow data from other catchments where long records have been collected (Laaha and Bloeschl, 2005).

3.4.1 Introduction

The regional analysis improves the capability to predict the water flow regime at gauged sites with short time series, reducing the uncertainties and moreover allows the estimation of the discharge properties at ungauged sites (Chokmani and Ouarda, 2004). In the regional analysis the data from all sites in a region are evaluated to define regions that are hydrologically homogeneous in terms of characteristic being studied. Regional analysis of extremes would require advances in the methodology of the statistics (Katz et al., 2002). The application of frequency analysis for hydrological extremes evaluation has a long history in hydrology.

The regionalisation regression approach was for the first time proposed in Dalrymple (1960), which considers the studied territory divided into a given number of homogeneous regions or zones, in which precipitations have the same probability distribution and an index variable defined for each location is the rescaling factor. Then it was applied to flood frequency analysis in tens of studies (Matalas et al., 1975, Gries and Wood, 1981; Stedinger, 1983; Arnell and Gabriele, 1985; Hosking et al., 1985a; Hebson and Cunnanne 1987). During the years it appears that the two-component extreme value (TCEV) distribution (Rossi F. et al., 1984), with its hierarchical

regionalisation procedure (Fiorentino et al., 1987; Gabriele and Arnell, 1991), based on the index variable method, is the best probabilistic model to be used for flood frequency analysis. The mean value of the annual maximum of daily rainfall is used as the index variable in numerous regionalisation procedures for flood flows (Rossi F. and Villani, 1994; Caporali and Tartaglia, 2000; Brath et al., 2003; Caporali et al., 2008).
There is an extensive literature on the application of probability distributions for prediction of flood frequencies. On the contrary, the number of studies reported on frequency of low flow is rather limited (Gottschalk et al., 1997). The regional regression approach was applied to low flow in more recent years and there is not a general agreement about how to perform it. Low flow behaviour differs from the flood frequency in many ways, mainly because it has not be possible till now to find a cumulative distribution function that is able to fit properly the low flow values for different sites. The methodology for regionalisation consisted of the following steps: selection and analysis of recorded data; discharge frequency analysis; definition of homogeneous regions; discharge estimation; evaluation of the procedure (Tucci et al., 1995). The basic procedure was described in the quoted studies for flood peak discharges and was modified in this study for the regionalisation of low flows. In this study is used the regional regression approach that in Cunnanne (1988) is defined as: regional only, ungauged catchment flow quantile estimation. In Fig. 3.3 the procedure proposed in this work is shown.

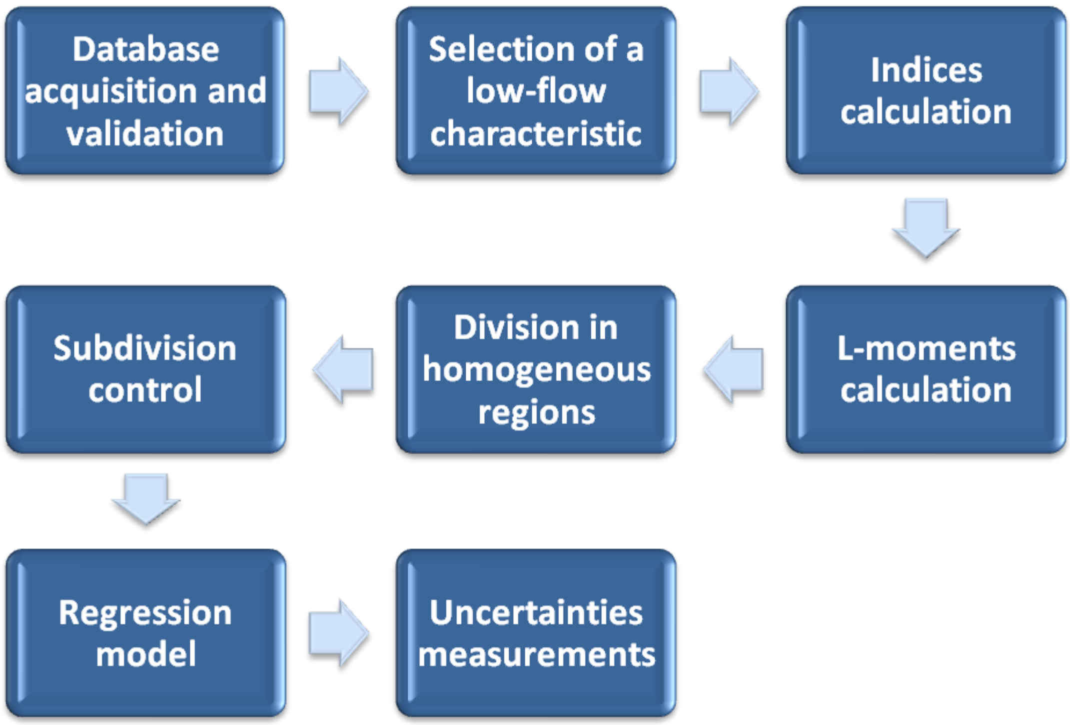


Figure 3.3 Proposed procedure for low flow regionalisation: steps in flow chart.

3.4.2 Area of study

The analysis is carried out on the discharge data recorded in several rivers in the Tuscany Region central Italy (Fig. 3.4). Tuscany is a region with an area of 23˙000 km^2 and 3˙600˙000 inhabitants (Regione Toscana et al., 2008). The minimum altitude is –3 m a.s.l. in the area of Massaciuccoli Lake, while the maximum altitude is 2˙037 m a.s.l. in Monte Prado (LU). The main rivers of the region are: Arno, Serchio, and Ombrone Grossetano. The Arno basin occupies one third of Tuscany's area. Moreover there are small basins of coastal rivers near the Tyrrhenian Sea and the upstream part of Tevere, Fiora and Magra watersheds. For these last inter-regional basins, no streamflow data are available for this study. The data used in the study were registered by Servizio Idrologico Regionale Toscano (Regional Hydrologic Service of Tuscany).

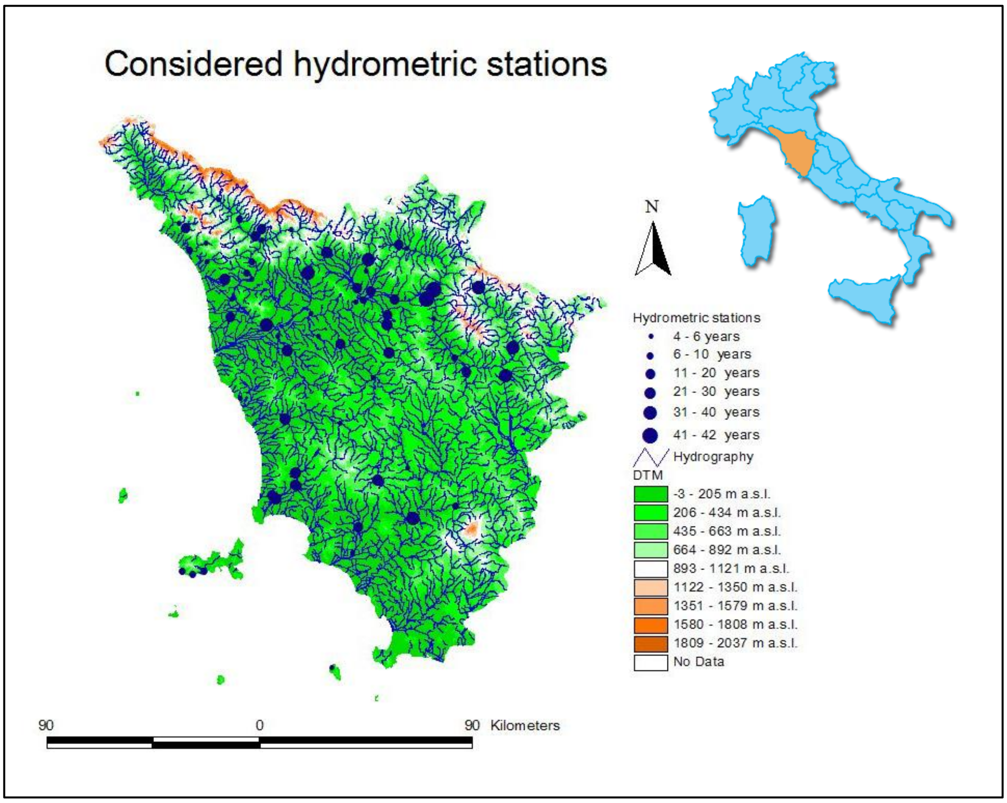


Figure 3.4 The Tuscany Region and the considered hydrometric stations with the years of registrations. In blue the hydrographic network.

3.4.3 Dataset

Choosing an appropriate concept to study droughts depends also on the time resolution of the available data and vice versa the most favourable time resolution depends on the purpose and outline of the study, the characteristics of the streams under study, the methods to apply, and the available computing tools. A daily time series contains more detailed information about the stream's discharge and about drought events, but also discharge series with a larger time interval can be favourable for various reasons. In general, local scale data records often have a resolution of days

or months and local studies are preferentially based on high resolution data, whereas studies with a larger spatial coverage and temporal extent are often based on time-aggregated seasonal or annual date (Stahl and Hisdal, 2004). For the considered stations daily data are available; moreover for most of them even data with a higher time resolution (15 minutes or 1 hour) are available. The daily data are used in this study because of the previous considerations about drought studies that need daily or monthly data and because they have a high spatial resolution in the considered period. On the other hand in a humid climate some streams might never experience multi-year drought. Annual data might not reveal even the most severe drought events. For example if an unusually dry summer is followed by an unusually wet winter, the mean annual discharge might not show any deviation from normal.
The dataset used in the study was registered by Servizio Idrologico Regionale Toscano (Regional Hydrologic Service of Tuscany) using data of the network previously managed by Ufficio Idrografico e Mareografico (Hydrographic and Mareographic Office) integrated with a new network.
At the moment Servizio Idrologico Regionale Toscano network measures:

- Wind speed and wind direction;
- Solar radiation;
- Precipitation;
- Temperature;
- Hygrometry;
- River stage and flow;
- Phreatimetric stage;
- River solid flow.

From these primary measures all the others are issued. The dataset collect data from more than 500 gauge stations that measure different hydrometric variables.

Figure 3.5 Nave di Rosano gauge station.

There are 326 stations with river stages or discharges data. In Fig. 3.5 a gauge station, Nave di Rosano, is shown.
Some of the records are only a few months long, or have totally discontinuous data. Only 121 stations, that had at least two years of data, were first selected for the analysis: 47 of these have only stage data, while 74 have stage data with a related stage–discharge rating curve. If discharge data are not present in the dataset, but stage records with associated stage-discharge rating curves are available, discharges are calculated. The operation is carried out for 9 stations: Carrara, Ruosina, Ponte Tavole auto, Camaiore auto, Camporgiano auto, Piaggione auto, Firenze Uffizi auto, Belvedere auto, and Pisa a Sostegno auto. For these stations the daily discharge data are calculated. Consequently their discharge data are considered. A total of 74 stations were preliminary selected for the analysis. Afterwards the stations "4270-Borgo a Mozzano" (633 daily values in 15 years) and "4720-Strette di Bifonica" (41 daily values in 9 years), were excluded from the analysis. Two or three years of further data were obtained resampling sub daily data of eight stations. An attempt to merge data of the automatic and analogical stations that are installed in the same river channel section is performed. This process is correct for most of the stations: when they registered at the same time, they collected the same data. Therefore it is possible to consider 9 automatic stations as part of the old ones. For the other two this process seems not correct. Indeed the two stations have the same spatial location but record different discharge values on the same day. In particular the stations "Subbiano" and "Subbiano Auto" worked contemporaneously for 7 years (registrations for the period 1st January 1992 – 31st January 2003 are shown in Fig. 3.6) and the stations "Ponte Ferrovia Fi-Roma" and "Ponte Ferrovia Fi-Roma auto" worked contemporaneously for 4 years.

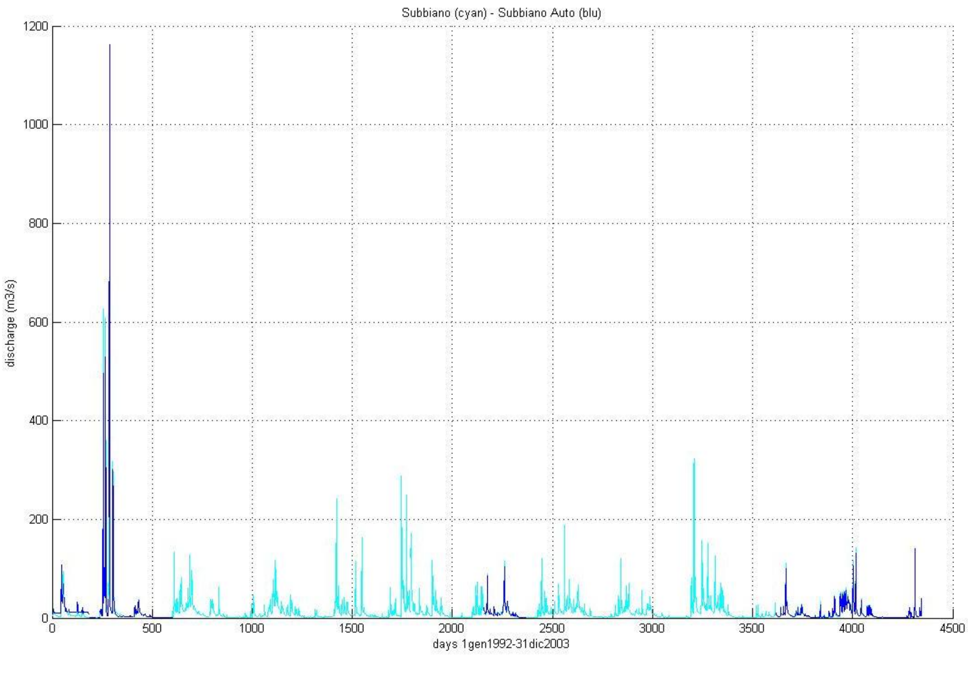


Figure 3.6 Registrations of the gauge stations "4410 Subbiano" (cyan) and "4411 Subbiano Auto" (blue) for the overlapping period 1st January 1992 – 31st January 2003.

The reason of the different values of registration is that these stations were employed to calibrate the new instruments, to verify the accuracy of the automatic stations and to set all the operational parameters. For this reason the old stations have to be used till the 31st December 2003 and the new ones from the 1st January 2004.
Not using stations with long periods of inactivity and merging the data of traditional analogical and digital automatic stations, when they are placed in the same location, a dataset of 65 stations was finally obtained (Fig. 3.7).

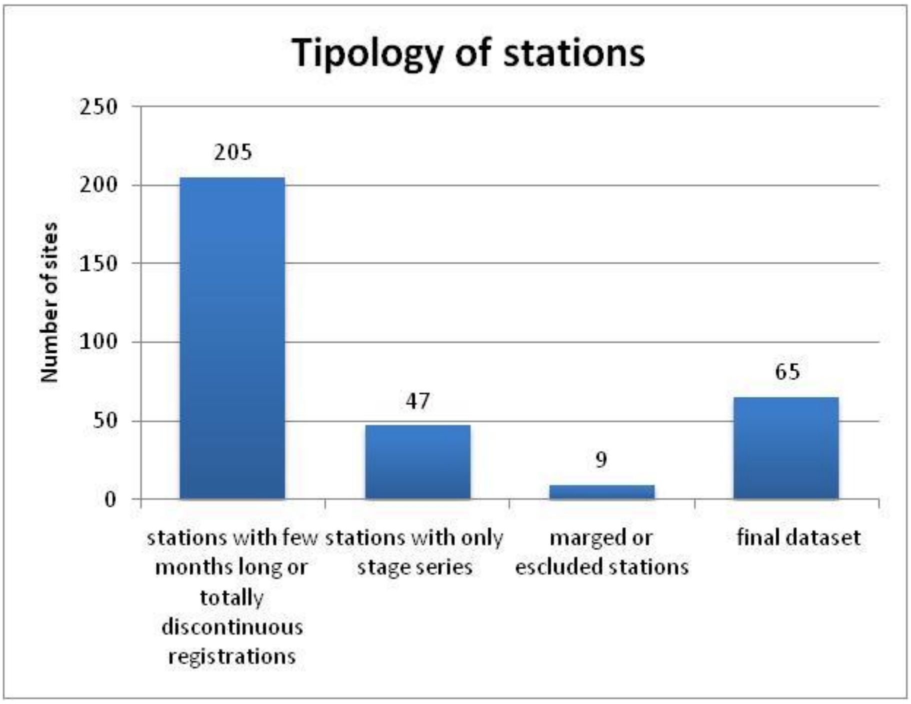


Figure 3.7 Dataset consistency.

Several stations had data from the 1930s, but the series were discontinuous and data were only collected during extreme high discharge events. Therefore only data after the 1949 were considered, except for the stations of “Nave di Rosano” (considered first year of registration 1931), “Subbiano” and “San Giovanni alla Vena” (considered first year of registration 1940). For the stations that are still registering, we considered data till the 31st December 2008.
The classification based on the years of recording is shown in Fig. 3.8. There are 13 stations that were activated in last years that have only 4 or 5 years of registrations and 52 stations with at least 6 years of data. The number of stations decreases if longer periods of registrations are required. “Fornacina” is the gauge station with the longest series of data (42 years).

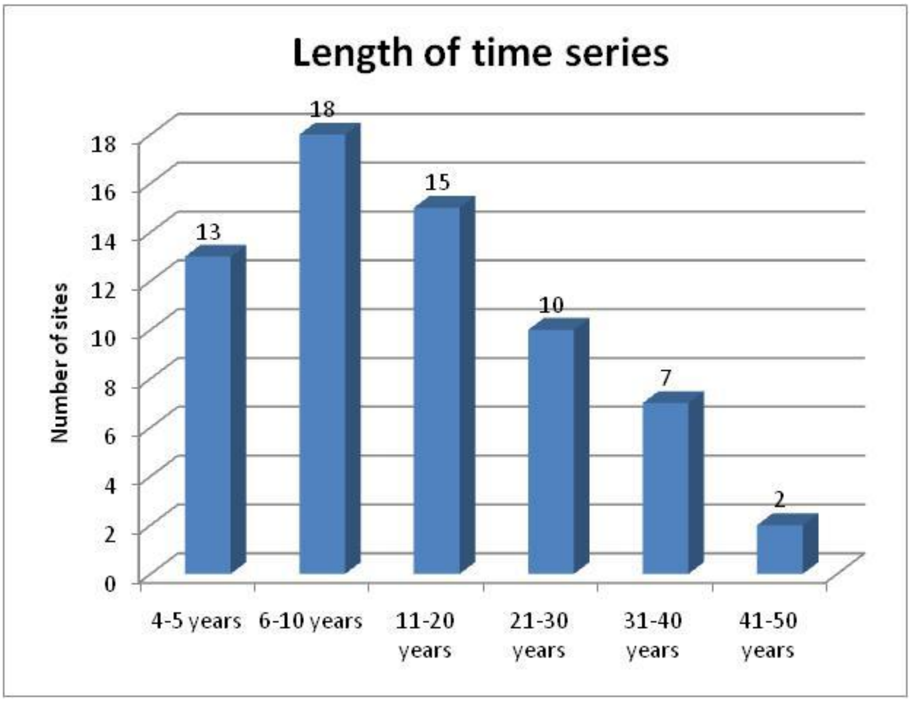


Figure 3.8 Length of time series of considered hydrometric stations.

In appendix A the main characteristics (X-UTM, Y-UTM, first year of registration, years of registration, catchment area, mean discharge, maximum registered discharge, Q70, Q90 and Q(7,2)) of the considered hydrometric stations are shown.
The number of stations used in the present study is sufficient for a good definition of homogeneous regions. Most of the previous studies about low flow frequency analysis estimation using some inferential methods that include some regionalisation aspects have used a relatively small number of sites: 18 rivers in central Italy by Castellarin et al. (2007), 20 flow gauge stations in Virginia by Tasker (1987), 23 rivers in Massachusetts by Vogel and Kroll (1989), 34 rivers across the United States of America by Matalas (1963), and 43 flow gauges in Brazil by Tucci et al. (1995).

3.4.4 Indices calculation

Different methods to derive streamflow characteristics are needed in order to characterize the whole range of hydrological droughts. Data from Servizio Idrologico Regionale Toscano were tested and various hydrological droughts indices were calculated (Tab. 3.4). Two kinds of low flow indices were chosen: the Q70, derived from the Flow Duration Curve – FDC (Fig. 3.9) and the Q(7,2), the smallest average discharge of 7 consecutive days within 2 years (Fig. 3.10). Q70 and Q(7,2) were subsequently standardised by the catchment area to make the low flow characteristic more comparable across scales. The resulting specific low flow discharges were considered to be representative of the characteristic unit runoff from the catchment area during sustained dry periods.

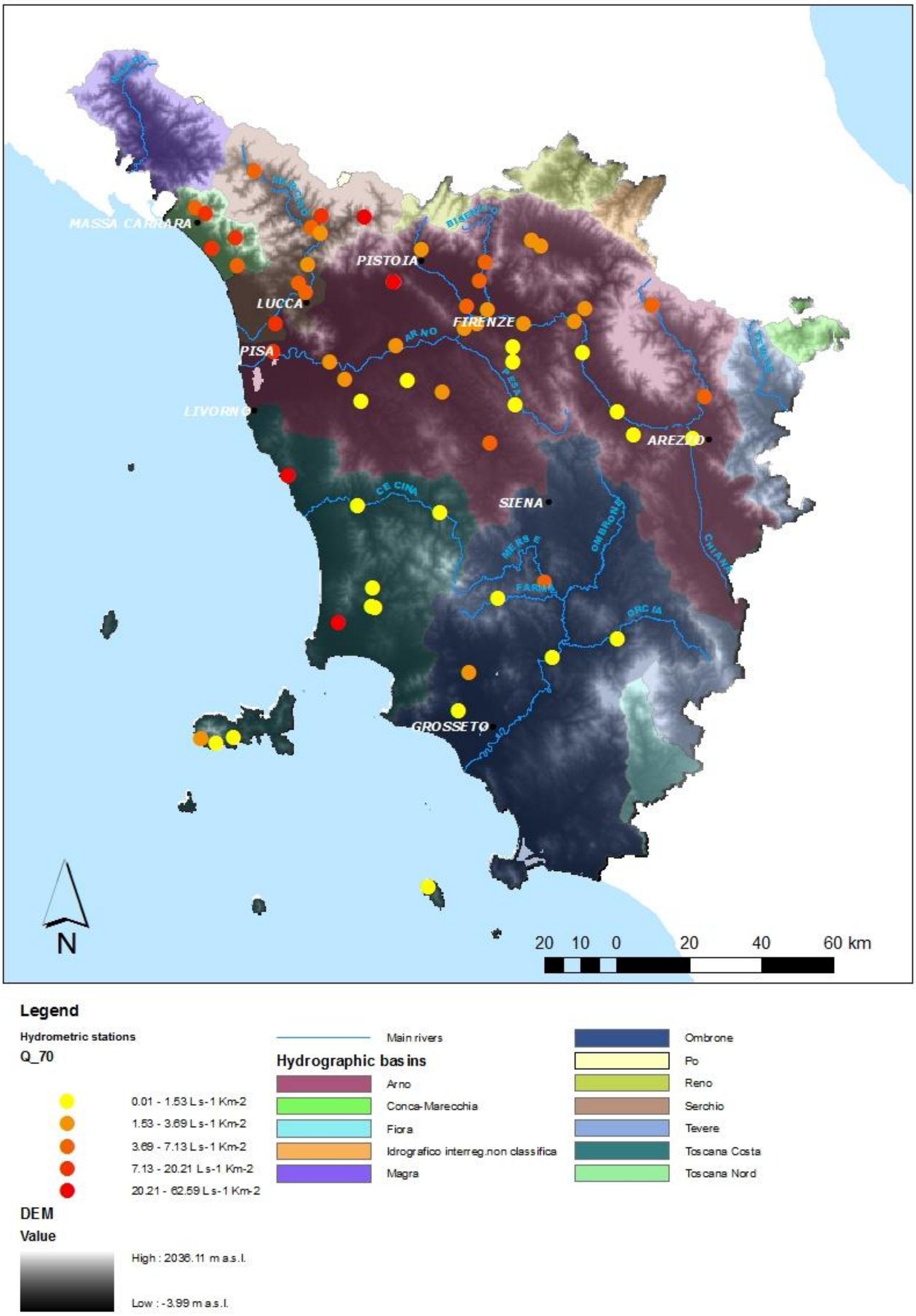


Figure 3.9 Q70 values in L s^{-1} km^{-2} at considered hydrometric stations. Hydrographic basins are underlined.

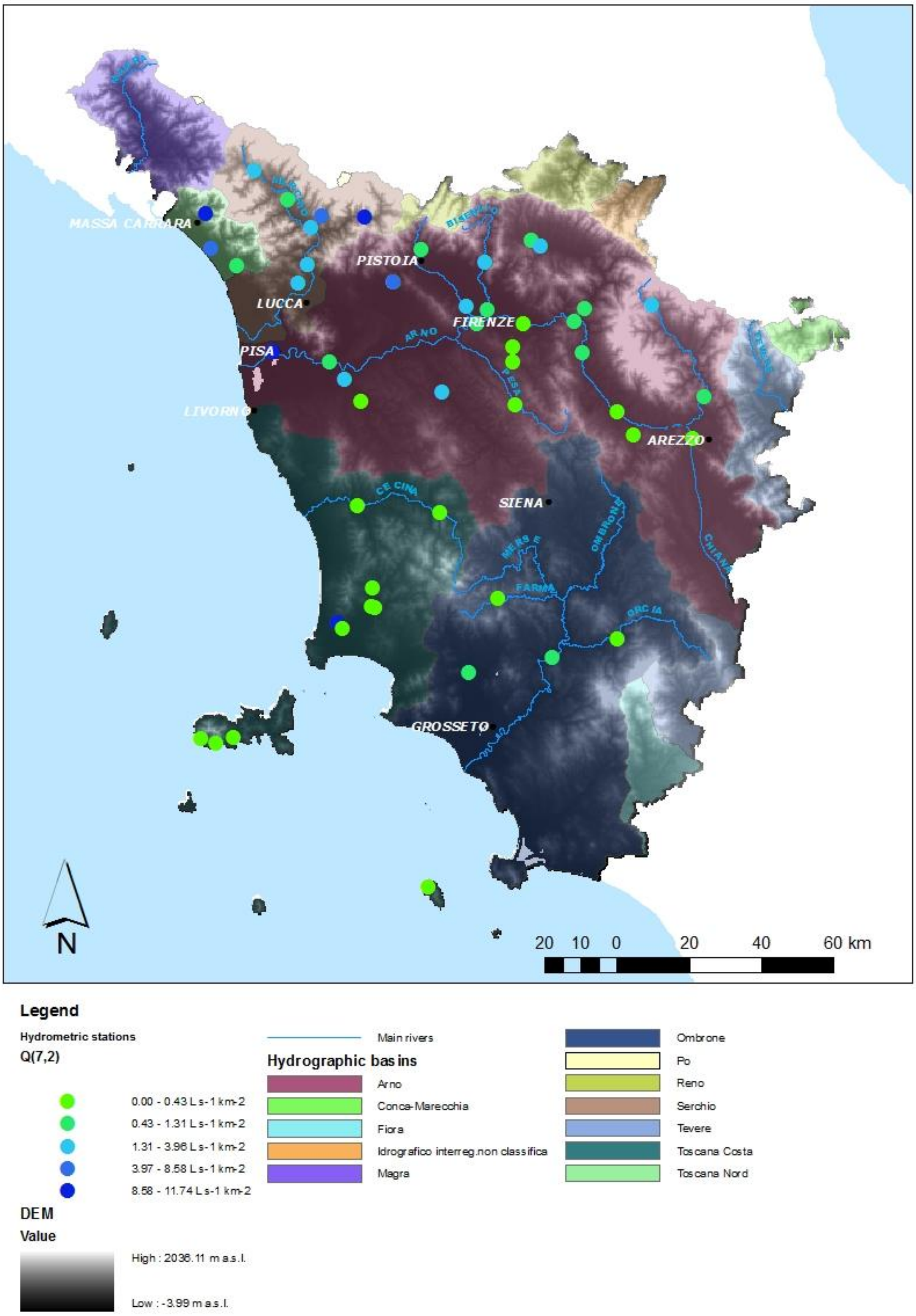


Figure 3.10 Q(7,2) values in L s^{-1} km^{-2} at considered hydrometric stations. Hydrographic basins are underlined.

Table 3.4 Statistical characteristics of low flow indices for the 65 considered catchments.

Index	unit	minimum	median	mean	maximum
Q70	**m^3/s**	0.000	0.543	4.265	118.933
Q90	**m^3/s**	0.000	0.185	2.934	102.982
Q(7,2)	**m^3/s**	0.000	0.129	2.444	92.138
Q70/A	**$l/(s*km^2)$**	0.000	2.241	5.940	62.592
Q90/A	**$l/(s*km^2)$**	0.000	0.998	3.196	56.678
Q(7,2)/A	**$l/(s*km^2)$**	0.000	0.655	2.062	11.744

3.4.5 Regionalisation regression approach

The aim of this study is to find hydrologically and statistically homogeneous regions in the area of interest, using standardized low flow characteristics from available observed streamflow records (1949–2008) for the Tuscany Region, central Italy. Following this, a low flow event regional frequency analysis, based on L-moments was carried out. The division into sub-regions was tested using discordancy and heterogeneity statistics. With this subdivision several interpolation techniques, either deterministic or geostatistical, such as Inverse Distance and Kriging, are applied. The results are valuated using the jackknife method. For each river section the catchment area is identified and an appropriate set of catchment physiographic and climatic characteristics is defined. A physiographical space-based method is used to relate the low flow indices to the investigated territory characteristics. The new space is built as a linear combination of the catchment geomorphologic and climatic characteristics. The root mean square error is assessed to compare the results, to quantify the accuracy of the different techniques and to define the most suitable procedure for low flow regionalisation.

3.4.6 Homogeneous regions

The regionalisation of streamflow characteristics in general is based on the premise that catchments with similar climate, geology, topography, vegetation and soils would normally have similar streamflow responses, for example, in terms of unit runoff from the catchment area, average monthly flow distribution, duration of certain flow periods, frequency and magnitude of high and low-flow events in similar sized catchments. If the study domain is large or very heterogeneous in terms of the low flow processes a number of authors have suggested splitting the domain into regions and applying a regression relationship to each of the regions independently. This is termed the regional regression approach. The first step in regionalisation studies is the delineation of hydrologically and statistically homogeneous regions. In some cases it is clear how to group a domain into regions of approximately uniform hydrological and statistical behaviour but, more often, the choice is far from obvious (Laaha and Bloeschl, 2006). Therefore a number of methods of identifying homogeneous regions have been proposed in the literature in the context of low flow regionalisation. All of these methods use low flow data and most of them use catchment characteristics as well. Some techniques and groups of techniques are here presented.

In the first technique, termed residual pattern approach, residuals from an initial, global regression model between flow characteristics and catchment characteristics are plotted. From them geographically contiguous regions are obtained by manual generalisation on a map (e.g. Hayes, 1991; Aschwanden and Kan, 1999). This is a method of improving on a global regression model. A drawback of the residual pattern approach, however, is that the initial model may be far from correct as it extends over the entire domain of interest. The shapes of the regions so obtained may then be artefacts of an inadequate model and the regional regression model will have little physical significance.

In the second group of techniques, multivariate statistics such as cluster analysis are used to delineate regions. In the Multivariate Analysis, both low flow data and catchment characteristics are used. They are usually standardized or weighted to enhance the discriminatory power of the methods. The use of multivariate statistics in the context of low flow regionalisation has been explored in detail by Nathan and McMahon (1990). They tested a number of approaches based on a combination of different techniques of cluster analysis, multiple regressions and principal component analysis. Since regions obtained by the cluster analysis approach are generally non-contiguous in space, the allocation of ungauged sites to the most similar group requires decision criteria, which are usually based on catchment characteristics.

A third group of techniques is based on the Classification and Regression Tree (CART) models (Breiman et al., 1984) which, to our knowledge, have not yet been used in low flow regionalisation. However, there do exist a number of interesting applications in hydrology, including the classification of satellite images of snow cover and the interpolation of ground snow measurement (e.g. Rosenthal and Dozier, 1996; Elder, 1995).

In a fourth technique, the seasonality of low flows is used to delineate homogeneous regions. The rationale of this approach is that differences in the occurrence of low flows within a year are a reflection of differences in the hydrologic processes and are hence likely to be useful for finding homogeneous regions. Merz et al. (1999) have illustrated that the seasonality approach is indeed useful in the context of flood frequency regionalisation in Austria (Laaha and Bloeschl, 2006).

A fifth technique is the use of L-moments applied to flow characteristics. It is used to subdivide areas into homogenous regions given a specific magnitude, i.e. maximum wind velocity (Modarres, 2007) and flow peaks (Parida et al., 1998; Kumar et al., 2003). It is based on useful statistics for regional frequency analysis, which measure regional homogeneity and goodness-of-fit and it is proposed by Hosking and Wallis (1993), based on L-moments method defined by Hosking (1990). L-moments method tries to solve the problem, present in all the previous methods, to produce substantial errors in the estimation of catchment area flow indices. This last technique is used in this work. The first two techniques are rejected because they give worst results than the chosen one, the fourth one is rejected because of the same seasonality of all the considered catchment areas, and the third one because it has never been applied to flows.

Homogeneous regions can be defined as geographically contiguous regions, geographically noncontiguous regions, or as hydrological neighborhoods. The delineation of contiguous regions may be accomplished using convenient boundaries based on geographic, administrative or physiographic considerations. The regions that result using such an approach may not always appear to be 'sufficiently' homogeneous. However, this pragmatic approach may appear to be suitable in conditions of limited data availability. A homogeneous region may therefore be viewed as a collection of catchments, which are similar in terms of catchment hydrological response, but not necessarily geographically contiguous (Smakhtin, 2001). To employ geographically contiguous regions is easier than using non-contiguous regions, especially in the context of scarcity of data. On the other hand, even two adjacent river catchments may have different topography, soils or other local anomalies (Laaha and Bloeschl, 2005).

In this work we decided to use contiguous regions and to delineate them using boundaries based on physiographic considerations. Low flow events are represented here by the 7-day annual minimum series and by the annual Q70 series. The L-moments approach is used to assign these data to the different regions, according to the homogeneity measures and climatic properties. Several different subdivisions are tested.

3.4.7 L-moments application

The L-moments approach by Hosking and Wallis (1997) is used in this work. L-moments are weighted linear sums of the expected order statistics and are analogous to conventional moments used to summarise the statistical properties of a probability function or an observed dataset. Recent hydrological studies on statistical analysis of annual maximum flood series have shown that L-moments are often superior to standard method of moment estimation techniques, particularly for regional studies. L-moments have theoretical advantages over conventional moments: they are more robust to the presence of outliers in the data, and are less subjected to bias in estimation (Gonzalez and Valdes, 2008). In a wide range of hydrologic applications, L-moments provide simple and reasonably efficient estimators of characteristics of hydrologic data (Saf, 2008). Even if this technique was proposed for the flood frequency analysis, it can easily be extended to other kind of hydrological variables (Modarres, 2008; Viglione et al., 2006). The L-moments are expectations of linear combinations of order statistics (Hosking, 1990) and are more robust to the data outliers and virtually unbiased for small samples. Moreover the L-moments have the very important advantage, over the conventional moments, of being less affected from the effects of sampling variability being linear functions of the data (Tartaglia et al., 2005).

Probability weighted moments (PMW), a generalization of the usual moments of a probability distribution, were introduced by Greenwood et al. (1979).The probability-weighted moments of a random variable X with distribution function $F(x) = P(X < x)$ are the quantities:

$$\beta_{p,r,s} = E[X^p \{F(X)\}^r \{1 - F(X)\}^s \tag{3.3}$$

where p, r, and s are real numbers. Probability weighted moments are likely to be most useful when the inverse distribution function x(F) can be written in closed form, for then we may write:

$$\beta_{p,r,s} = \int_0^1 \{x(F)\}^p F^r \{1 - F\}^s dF \tag{3.4}$$

and this is often the most convenient way of evaluating these moments. There are several distributions (for example, the Gumbel, logistic, and Weibull) whose parameters can be conveniently estimated from their probability weighted moments (Hosking et al., 1985).

Hosking and Wallis (1993) extended the use of L-moments and developed useful statistics for regional frequency analysis which measure discordancy, regional homogeneity and goodness of fit.

The theoretical expressions of the L-moments are defined by Hosking (1990) as linear combinations of the Probability Weighted Moments (PWM). Following Hosking's (1990) definition, let X be a real-value random variable with cumulative distribution function $F(x)$ and quantile function $x(F)$, then the L-moments of X are:

$$\lambda_r = r^{-1} \sum_{k=0}^{r-1} (-1)^k \binom{r-1}{k} EX_{r-k:r} \qquad \text{with } r = 1, 2, \ldots \tag{3.5}$$

The L in L-moment emphasizes that λ_r is a linear function of the expected order statistics. Furthermore the natural estimator of λ, based on an observed sample of data is a linear combination of the ordered data values. Substituting in the previous expression the expectation of an order statistic we obtain the expression:

$$\lambda_r = \int_0^1 x(F) \;\; P_{r-1}(F) \;\; dF \qquad \text{with } r = 1, 2, \ldots \tag{3.6}$$

The first four moments are:

$$\begin{aligned}
\lambda_1 &= EX && = \beta_0 \\
\lambda_2 &= 1/2E(X_{2:2} - X_{1:2}) && = 2\beta_1 - \beta_0 \\
\lambda_3 &= 1/3E(X_{3:3} - X_{2:3} + X_{1:3}) && = (6\beta_2 - 6\beta_1 + \beta_0) \\
\lambda_4 &= 1/4E(X_{4:4} - X_{3:4} + X_{2:4} - X_{1:4}) && = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0
\end{aligned} \tag{3.7}$$

where:

$$\beta_i = \int_{-\infty}^{+\infty} x \cdot F_X(x)^i \, dF(x) = \int_{-\infty}^{+\infty} x \cdot F_X(x)^i \cdot f(x) dx \tag{3.8}$$

is the *i*-th PWM. The first L-moment is the mean. The second L-moment measures the scale or the dispersion of the distribution. The third L-moment is the central second difference of the median of the sample. It is a measure of the skewness. Symmetric distributions have the third moment equal to zero. The fourth L-moment is a measure of distribution kurtosis, as well as the fourth conventional moment. Dimensionless parameters to evaluate the skewness and kurtosis are τ_3 and τ_4, defined as the ratio between the relative L-moment and the second L- moment.

$$\tau_i = \frac{\lambda_i}{\lambda_2} \qquad \text{with i = 3, 4...} \tag{3.9}$$

Following these definitions, it is possible to define:

- L-location λ_1 (first L-moment),
- L-scale λ_2 (second L-moment),
- L-skewness τ_3 (ratio second L-moment /third L-moment),
- L-kurtosis τ_4 (ratio second L-moment/fourth L-moment).

It is defined even the L-coefficient variation *L-cv* as:

$$\tau = \frac{\lambda_2}{\lambda_1} \tag{3.10}$$

In practice L-moments are usually estimated from a random sample drown from an unknown distribution. Because λ_r is a function of the expected order statistics of sample size r, it is natural to estimate it with the corresponding function of the sample order statistics averaged over all subsamples of size r which can be constructed from the observed sample size n. The first four sample L-moments are calculated with 3.11 equations.

$$l_1 = n^{-1}\sum_i x_i$$

$$l_2 = \frac{1}{2}\binom{n}{2}^{-1} \sum_i \sum_j (x_{i:n} - x_{j:n}) \tag{3.11}$$

$$l_3 = \frac{1}{3}\binom{n}{3}^{-1} \sum_i \sum_j \sum_k \; (x_{i:n} - 2x_{j:n} + x_{k:n})$$

$$l_3 = \frac{1}{4}\binom{n}{4}^{-1} \sum_i \sum_j \sum_k \sum_l \; (x_{i:n} - 3x_{j:n} + 3x_{k:n} - x_{l:n})$$

With $i > j > k > l$. The described method is applied to the Tuscany region dataset. The L-moments of the 7-day annual minimum series are calculated for all the stations with at least 6 years of registration. The discordancy and heterogeneity parameters to evaluate the regional homogeneity are used on the *AM(7)* normalized by the catchment area to test different sub-divisions hypothesis. Even the L-moments for the other selected low flow indices Q70, always normalized by the catchment area, are calculated. Results for considered hydrometric stations are shown in Tab. 3.5.

Table 3.5 First four sample L-moments calculated for Q(7,2) and Q70 at the considered hydrometric stations.

Code	Q(7,2) - l_1	Q(7,2) - l_2	Q(7,2) - l_3	Q(7,2) - l_4	Q70 - l_1	Q70 - l_2	Q70 - l_3	Q70 - l_4
4010/4011	21.7695	5.7758	1.4189	1.6444	9.7891	2.9755	0.2726	1.0908
4045	21.8164	9.6833	-0.424	-1.7881	10.8629	5.398	0.8992	-0.5874
4059	5.5393	1.9924	0.1684	0.5339	1.5552	1.2331	0.9587	0.8716
4115	30.7295	24.1955	12.9679	-1.6825	0.873	0.4093	-0.0319	-0.0723
4195	5.7422	1.4054	0.3995	0.162	3.8685	0.6767	0.2246	0.2519
4200	23.3449	7.6252	2.69	2.104	9.8009	3.3718	1.65	2.0057
4231	40.2927	12.6533	0.6455	0.9613	9.4685	3.868	-0.2688	-0.0629
4284	4.2535	1.4104	0.2889	-0.0936	3.248	1.1072	0.4517	-0.0463
4286	5.6471	1.8295	-0.1099	-0.0837	3.446	1.3596	-0.0858	0.2637
4379/4380	7.6362	3.1506	1.2623	0.8717	1.8926	0.8107	0.1825	0.123
4410/4411	4.5435	1.5226	0.2774	0.0089	2.481	1.2893	0.6256	0.3333
4520/4521	0.8018	0.3326	0.1751	0.1362	0.2492	0.0985	0.0453	0.0342
4568	0.8081	0.2753	0.1077	0.0754	0.1886	0.0777	0.0485	0.0292
4723	0.9059	0.2755	0.0391	0.0303	0.0998	0.0654	0.0188	-0.0102
4779/4780	5.6613	1.3153	0.2514	0.2485	2.7481	0.8147	0.2484	0.1353
4791	2.4803	0.5909	0.0277	0.0724	0.5871	0.1796	0.0233	0.0272
4811	1.8423	0.438	-0.1024	0.0731	0.8689	0.2177	-0.1432	0.0801
4860	4.0406	1.0378	0.1294	0.1229	1.2107	0.2595	0.0691	0.0183
4875	4.8191	0.6759	-0.0311	-0.0168	2.6569	0.6893	0.1995	0.0595
4910	1.3476	0.6233	0.2375	0.1278	0.3199	0.1455	0.0679	0.0302
4970	3.0164	0.4907	-0.0012	0.0594	1.9788	0.3486	-0.0127	0.0416
5040	2.7236	1.6925	0.9169	0.5441	1.0887	1.0326	0.9268	0.7832
5050	39.9308	11.4547	2.5216	3.6703	12.6104	6.1135	1.9647	0.8293
5130/5131	0.8776	0.4364	0.2513	0.2114	0.1753	0.079	0.0296	0.0154
5161	2.6946	0.9669	0.4329	0.5859	1.2802	0.4088	-0.2057	0.0267
5190	2.1771	0.5153	0.0835	0.0489	0.7967	0.152	0.0141	0.0313
5231	14.503	0.2457	-0.0119	0.0318	11.4211	0.8308	0.1129	0.0626
5372	0.3992	0.2124	0.1029	0.0849	0.0628	0.0281	0.0063	-0.0004
5400/5401	0.4365	0.2269	0.1016	0.0571	0.1017	0.0616	0.0418	0.0344
5448	19.7222	4.4692	0.7731	0.1078	7.1272	1.6145	0.4273	0.1103
5460	0.3857	0.1543	0.0647	0.06	0.0268	0.025	0.0217	0.0173
5470/5471	0.4894	0.2104	0.0783	0.0626	0.0564	0.0372	0.0229	0.0233
5485	0.1525	0.1337	0.1072	0.0868	0.0628	0.0281	0.0063	-0.0004
5610	3.1773	0.5651	0.2776	0.2179	0.9962	0.5205	0.1254	0.1029
5720	1.0403	0.3878	0.1314	0.0736	0.3124	0.085	0.0076	0.0046
5760	0.5555	0.1981	0.0301	0.0347	0.0289	0.0248	0.0178	0.0097

Continued

Code	Q(7,2) - l_1	Q(7,2) - l_2	Q(7,2) - l_3	Q(7,2) - l_4	Q70 - l_1	Q70 - l_2	Q70 - l_3	Q70 - l_4
5790/5791	1.4609	0.2887	0.0536	0.0795	0.6298	0.1435	0.011	-0.002
5930	1.9054	0.3357	-0.0905	0.0463	0.1555	0.1375	0.1063	0.0695
5940	1.5172	0.4701	0.0108	0.1037	0.0928	0.0829	0.0653	0.0442
5960	0.3625	0.0725	-0.0725	0.0725	0.075	0.0643	0.0452	0.0222

In the regional flood frequency modelling various sites of a region are grouped together for estimation of regional parameters. Initially Darlymple (1960) provided a homogeneity test to check the homogeneity of a region. Hosking and Wallis (1993 and 1997) extended the use of L-moments and developed useful statistics for regional frequency analysis, in particular the Discordancy and Heterogeneity parameters to evaluate the regional homogeneity (Jaiswal et al., 2003).

Given a group of sites the aim is to identify those sites that are discordant with the group as a whole. Four parameters, belonging to two different groups, are evaluated. The first one is the Discordancy statistics, measured in terms of the first four L-moments of the sites' data. The other three parameters that measure the homogeneity of a region, the Heterogeneity statistics, are relative respectively to the first, first and second, first and third L-moment (Hosking and Wallis, 1993).

Discordancy is calculated starting from L-moments ratios representing coefficients of variation, skewness and kurtosis (*L-cv, L-sk* and *L-ku*) of a site. They are considered as the coordinates for each gauge station in a three dimensional space. A group of homogeneous sites gives a cloud of nearby points. Any point that is far from the centre of the cloud is discordant. The statistic to evaluate the distance of a point is the Discordancy measure. Let $\boldsymbol{u} = [L - cv^{(i)}\ L - sk^{(i)}\ L - ku^{(i)}]$ be a vector with the values for the *i*-site. Let:

$$\bar{u} = N^{-1}\sum_{i=1}^{N} u_i \tag{3.12}$$

and $\boldsymbol{S}$ be the covariance matrix, the discordancy for the site *i* is defined as:

$$D_i = 1/3\ (u_i - \bar{u})^T S^{-1}(u_i - \bar{u}) \tag{3.13}$$

Two uses of the discordancy measure are possible. First, at the outset of the analysis it may be applied to a large group of sites, all those within some large geographical area. The idea is that sites with gross errors in their data will stand out from the other sites and be flagged as discordant. Sites individuated as discordant should be checked to find errors in recording or transcription of data. Later in the analysis, when homogeneous regions have been at least tentatively identified, the discordancy measure can be calculated for each site in the proposed region. If any site is then discordant with the region as a whole, the possibility of moving that site to another region should be considered. However a site's L-moments may differ by chance alone from those of other similarly sites: for example if an extreme but localized meteorological event may have affected only once few sites in a region. Large values of D_i indicate sites that are most discordant from the group. It is not easy to choose a single value of D_i that can be used as a criterion for deciding whether a site is unusual. In this work, following Hosking ad Wallis (1993) a site is considered to be unusual if the Discordancy measure (D_i) is larger than 3 and possibly discordant if D_i is larger than 2.

The homogeneity test proposed by Hosking and Wallis (1993; 1997) assesses the homogeneity of a group of sequences at three different levels by focusing on three measures of dispersion for different orders of the sample L moment ratios.

A measure of dispersion for the coefficient of L variation, *L-Cv* is:

$$V_1 = \frac{\sum_{i=1}^{R} n_i (t_{2(i)} - \overline{t_2})^2}{\sum_{i=1}^{R} n_i} \tag{3.14}$$

A measure of dispersion for both the *L-Cv* and the L-skewness coefficients in the *L-Cv*–L-skewness space is:

$$V_2 = \frac{\sum_{i=1}^{R} \sqrt{n_i (t_{2(i)} - \overline{t_2})^2 + (t_{3(i)} - \overline{t_3})^2}}{\sum_{i=1}^{R} n_i} \tag{3.15}$$

A measure of dispersion for both the L-skewness and the L-kurtosis coefficients in the L-skewness–L-kurtosis space is:

$$V_3 = \frac{\sum_{i=1}^{R} \sqrt{n_i (t_{3(i)} - \overline{t_3})^2 + (t_{4(i)} - \overline{t_4})^2}}{\sum_{i=1}^{R} n_i} \tag{3.16}$$

where $\overline{t_2}$, $\overline{t_3}$, and $\overline{t_4}$ are the group mean of *L-cv*, L-skewness, and L-kurtosis, respectively; $t_{2(i)}$, $t_{3(i)}$, $t_{4(i)}$, and n_i are the values of *L-cv*, L-skewness, L-kurtosis and the sample size for site *i*; and R is the number of sequences.

The underlying concept of the test is to measure the sample variability of the L-moment ratios and compare it to the variation that would be expected in a homogeneous group. The expected mean value and standard deviation of these dispersion measures for a homogeneous group, μ_{Vk}, and σ_{Vk}, respectively, are assessed through repeated simulations, by generating homogeneous groups of basins having the same record lengths as those of the observed data following the methodology proposed by Hosking and Wallis (1990). The simulation is performed by fitting a Kappa distribution with four parameters to the regional data set. The Kappa distribution has several useful attributes for conducting homogeneity tests. As a generalization of the generalized logistic, generalized extreme-value, and generalized Pareto distributions, it serves as a candidate distribution when these three-parameter distributions give an insufficient fit, or when the investigator is not limited to the use of a particular three-parameter distribution. The four parameter Kappa distribution is used to generate synthetic data for evaluating the goodness-of-fit of different distributions. The heterogeneity measures are then evaluated using the following expression:

$$H_k = \frac{V_k - \mu_{Vk}}{\sigma_{Vk}} \qquad \text{for k = 1, 2, 3.} \tag{3.17}$$

The three obtained statistics (*Hi*) are *H1*, *H2* and *H3* respect to *L-cv* scatter, *L-cv–L-sk* and *L-cv–L-ku*.

Large values of *Hi* indicate region with sites that are really discordant from the group. A region is homogenous if any of the *Hi* values is less than 1, possibly heterogeneous if *Hi* is between 1 and 2, and definitely heterogeneous if *Hi* is more than 2 (Hosking and Wallis, 1993).

3.4.8 Division into sub-regions

The described method is applied to the Tuscany region dataset. The L-moments for the two selected low flow indices were calculating and once the area of interest is divided into different regions, geographically contiguous, the homogeneity measures are calculated to test each subdivision. Proceeding by trial-and-error some sub-basins were moved from one region to another, and some regions were split into sub-regions to reach the best possible homogeneity. The discordancy (D_i) and the heterogeneity (*H1, H2,* and *H3*) are calculated firstly for the whole area considered as a unique region. Values of calculated homogeneity statistics suggested that this approximation was not correct. In particular 5 stations have values of Discordancy higher than 3 (Tab. 3.6), the threshold value of the discordancy measure and *H1* for the whole region has a value that is considerably higher than 2, the threshold levels to consider a region "definitely heterogeneous". The area is successively split into three different sub-regions, following previous studies on rainfall extreme values (Tartaglia et al., 2006; Caporali et al., 2008). With this subdivision there is some homogeneity, but some stations still present high values of discordancy. Only the North sub-region has a value of *H1* that is above the "definitely heterogeneous" threshold level. Finally a new subdivision into 5 sub-regions was proposed (Fig. 3.11), splitting the central and the northern regions of the previous subdivision. Some stations are moved from one sub-region of the previous subdivision to another one. Once the gauge stations belonging to the same sub-region are individuated, the different sub-regions are delimitated following the main hydrological watersheds. The station of Colonna is not included in the subdivision, due to non-homogeneity of its data. With this subdivision the regions are more homogeneous, and the subdivision follows hydrological and precipitation features. The previous subdivisions are tested even with the annual Q70 values (Tab. 3.7). Due to the homogeneity of these values, the subdivision into three regions seems sufficient and, since that only North and Centre sub-regions are above the "possibly heterogeneous" threshold levels and no stations have a D_i value above 3. The subdivision into five sub-regions gives anyway better results.

Table 3.6 Values of the homogeneity parameters for the 7-day annual minimum series. In **red** are shown the parameters that define a "definitely heterogeneous region", in **blue** the ones that define a "possible heterogeneous" region.

Regions	Number of stations	*H1*	*H2*	*H3*	Number of sites *D*>2	Number of sites *D*>3
Unique	48	**3.89**	0.99	**1.58**	**9**	**5**
North	21	**2.13**	**1.25**	**1.62**	**4**	**2**
Centre	21	**1.58**	0.99	**1.71**	**4**	**2**
South	6	**1.63**	0.70	0.94	**1**	0
North East	11	0.43	0.74	0.34	**1**	0
North West	9	**1.22**	0.79	**1.36**	**1**	**1**
Centre East	11	**1.16**	0.77	0.96	0	0
Centre West	9	**1.80**	0.85	**1.33**	**3**	0
South	7	**1.60**	0.77	0.95	0	0

Table 3.7 Values of the homogeneity parameters for the Q70 annual series. In **red** are shown the parameters that define a "definitely heterogeneous region", in **blue** the ones that define a "possible heterogeneous" region.

Regions	Number of stations	*H1*	*H2*	*H3*	Number of sites *D*>2	Number of sites *D*>3
Unique	48	**2.22**	0.66	0.90	**3**	**2**
North	21	**1.43**	0.64	0.87	0	0
Centre	21	**1.03**	0.59	0.89	**1**	0
South	6	0.81	**1.04**	0.97	**1**	0
North East	11	0.27	0.31	0.31	0	0
North West	9	**1.28**	0.52	0.76	0	0
Centre East	11	0.60	0.41	0.61	0	0
Centre West	9	**1.38**	0.61	0.76	**2**	0
South	7	0.70	0.88	0.84	0	0

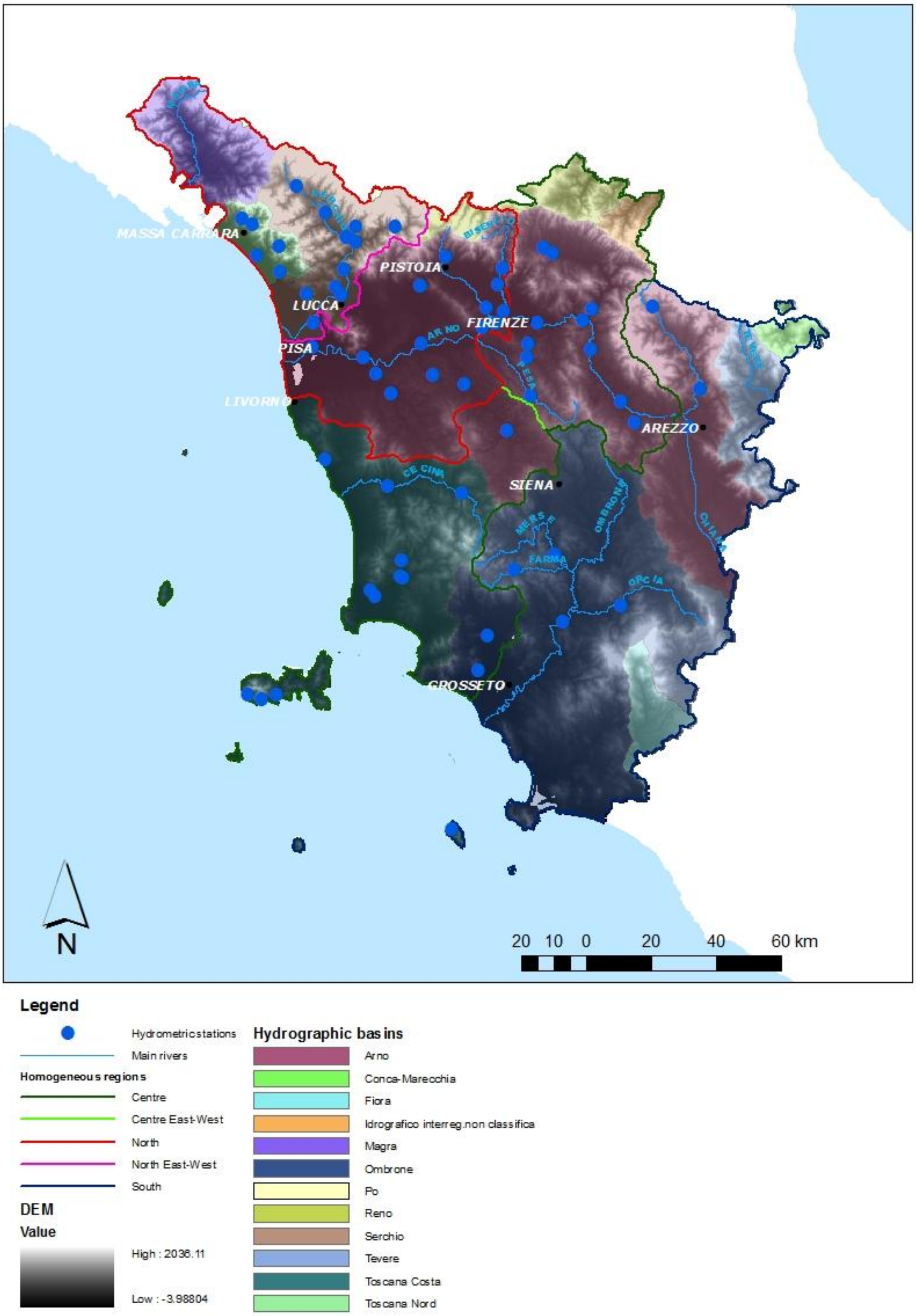


Figure 3.11 Final subdivisions into hydrologically and statistically homogeneous regions.

3.4.9 IDW and Universal Kriging interpolation techniques of low flow indices at ungauged basins

Flood indices at a given site represent the hydrological response to the prevailing climate and reflect the signature of the basin's physical and geomorphological characteristics. Therefore an appropriate interpolation technique over the geographical or physiographical space may have a real potential for the regionalisation of hydrological variables. Indeed, while they are discontinues in the geographical space, indices can be regarded as continuous variables in the physiographical space. In other terms, it is possible to estimate flow indices at an ungauged site, knowing flow indices at gauged sites in the same sub-region, and by using an appropriate interpolation technique (Chokmani and Ouarda, 2004).

The first considered interpolation technique is the Inverse Distance Weighted (IDW) interpolation. Inverse distance weighted methods are based on the assumption that the interpolating surface should be influenced most by the nearby points and less by the more distant points. The interpolating surface is a weighted average of the scatter points and the weight assigned to each scatter point diminishes as the distance from the interpolation point to the scatter point increases.

The simplest form of inverse distance weighted interpolation is the Shepard's method (Shepard, 1968). The equation used is as follows:

$$F(x,y)=\sum_{i=1}^{n} w_i f_i = \sum_{i=1}^{n} \frac{h_i^{-2}}{\sum_{j=1}^{n} h_j^{-2}} f_i \tag{3.18}$$

where n is the number of scatter points in the set, f_i are the prescribed function values at the scatter points (e.g. the data set values), w_i are the weight functions assigned to each scatter point, and h_i is the distance from the scatter point to the interpolation point or:

$$h_i=\sqrt{(x-x_i)^2+(y-y_i)^2} \tag{3.19}$$

where (x, y) are the coordinates of the interpolation point and (x_i, y_i) are the coordinates of each scatter point. The weight function varies from a value of unity at the scatter point to a value approaching zero as the distance from the scatter point increases. The weight functions are normalized so that the weights sum to unity.

Some resampling procedures are evaluated to compare the obtained results. Resampling methods are becoming increasingly popular as statistical tools, as they are generally very robust, their simplicity is compelling, and their computational demands are no longer an issue to their widespread implementation. These methods involve either sampling or scrambling the original data numerous times, and we consider three general approaches here. Randomization tests involve taking the original data and either scrambling the order or the association of the original data. Jackknife estimates involve computing the statistic of interest for all combinations of the data where one (or more) of the original data points are removed. Bootstrap approaches attempt to estimate the sampling distribution of a population by generating new samples by drawing, with replacement, from the original data. This last method, even if became really popular in hydrologic studies in the last years, is not applicable because of the small size of the considered hydrometric stations.

Tukey (1958) suggested a simple approach, jackknife estimates, based on removing data and then recalculating the estimator provides a general purpose statistical tool that is both easy to implement and solves a number of problems.

Suppose we wish to estimate some parameter θ as a potentially very complex statistic of the n data points,

$$\hat{\theta} = \varphi(x_1, x_2, \dots, x_{i-1}, x_i, x_{i+1}, \dots, x_n) \tag{3.20}$$

let the jth partial estimate of θ be given by the estimate computed with data point x_j removed,

$$\widehat{\theta_{-J}} = \varphi(x_1, x_2, \dots, x_{i-1}, x_{i+1}, \dots, x_n) \tag{3.21}$$

The jth pseudovalue is defined by:

$$\widehat{\theta_J^*} = n\hat{\theta} - (n-1)\widehat{\theta_{-J}} \tag{3.22}$$

These pseudo-values assume the same role as the x_j in estimating the mean; hence the jackknife estimate of θ is given by the average of the pseudo-values,

$$\widehat{\theta^*} = \frac{1}{n}\sum_{i=1}^{n}\widehat{\theta_i^*} \tag{3.23}$$

The major motivation for many jackknife estimates is that they reduce bias. In particular, Quenouille (1956) showed that using a jackknife estimate removes bias of order $1/n$.

The jackknife procedure is used to evaluate the root mean square error, RMSE. The RMSE is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_i - \hat{z}_i)^2} \tag{3.24}$$

where z_i, and $\hat{z}_i$ are, respectively, the local and regional estimates at station i of the hydrological variable of interest; n is the sample size.

The RMSE is calculated for the three proposed subdivisions and for both the proposed low flow indices (Tab. 3.8). Results confirm the good properties of homogeneity of the final subdivision for three sub-regions (South, Centre East, and Centre West) while for other two (North East and North West) the results are not the expected ones. For the North East region it probably depends on the variability of the values while for the North West region for the different geo-climatic characteristics that are not taken into account with this interpolation. In Fig. 3.12 the calculated values using the different subdivisions are compared with the observed ones.

Table 3.8 Values of the RMSE - Root Mean Square Error for IDW interpolations.

Subdivision	Regions	RMSE Q(7,2)	RMSE Q70
Unique	Unique	3.19	9.25
3 regions	North	4.02	13.44
	Centre	2.61	3.72
	South	0.75	2.26
5 regions	North East	4.14	15.20
	North West	4.10	10.76
	Centre East	0.58	0.64
	Centre West	0.63	0.86
	South	0.70	2.08
	Mean	2.76	8.96

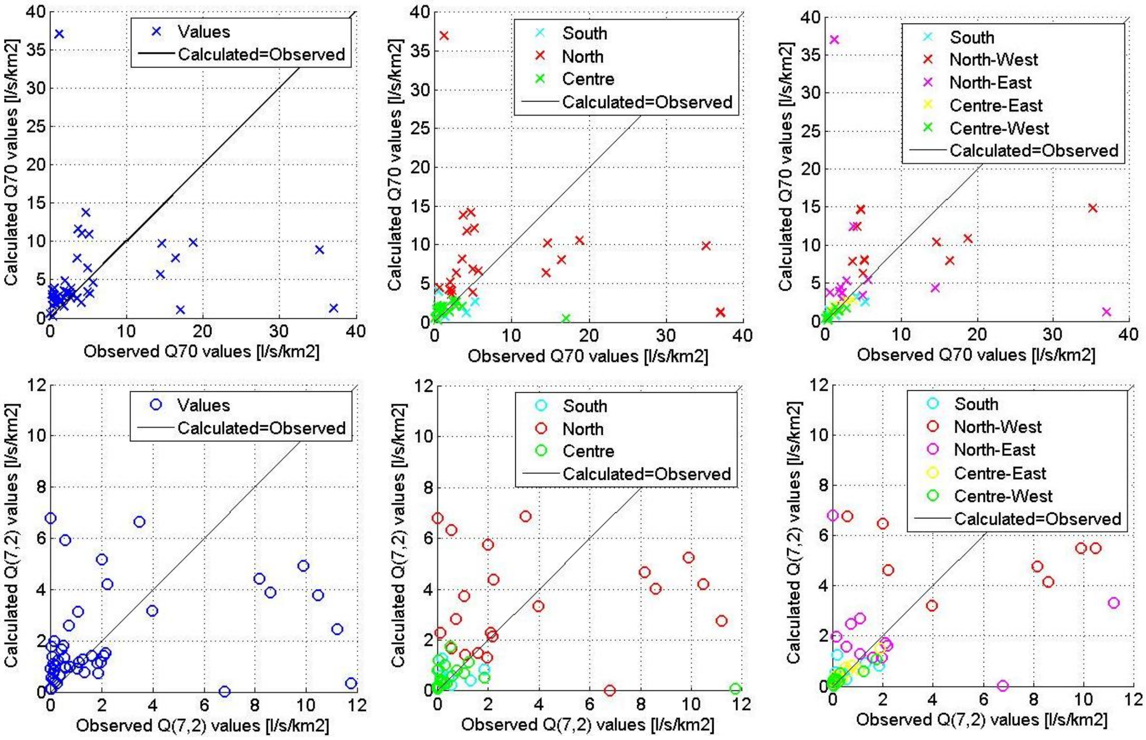


Figure 3.12 Observed versus calculated Q70 values (above) for a unique region (left), 3 regions (centre), and 5 regions (right); observed versus calculated values for Q(7,2) values (below) for an unique region (left), 3 regions (centre), and 5 regions (right).

The second considered interpolation technique is a geostatistical method, the Ordinary Kriging. Geostatistical methods are powerful statistical techniques designed to study spatially autocorrelated variables (Isaaks and Srivistava, 1989). They permit estimating the local value of a variable using sparse local measurements.

Kriging is based on the assumption that the parameter being interpolated can be treated as an intermediate between a truly random variable and a completely deterministic variable. In fact it varies in a continuous manner from one location to the next and therefore points that are near each other have a certain degree of spatial correlation, but points that are widely separated are statistically independent. These techniques take into account the spatial structure and distribution of the variables through tools known as structure functions such as variograms, covariograms or correlograms. These structure functions express the covariance between the observed points according to the distance which separates them. They describe the intensity and the pattern of the variable spatial autocorrelation. Ordinary Kriging, the most popular geostatistical technique, produces an unbiased and optimal linear estimation of the unknown values. Thus it provides the best possible estimate using neighbourhood information. The estimate is obtained by weighting each neighbouring value. With respect to the spatial structure, the closest values receive higher weights because they are more likely to be similar to the unknown value being estimated. The unbiasedness is ensured by the universal condition where the sum of the weighting coefficients is equal to 1 (Chokmani and Ouarda, 2004). The kriging estimation can be expressed as follows:

$$\begin{cases} Z^*(x_0) = \sum_{i=1}^{n} w_i Z_i \\ \sum_{i=1}^{n} w_i = 1 \end{cases} \tag{3.25}$$

where Z is the continuous variable of interest, $Z^*(x_0)$ its value being estimated at the unsampled position x_0, Z_i its known values at the n sampled locations x_i and w_i are the corresponding weighting coefficients. The exact weighting coefficients are calculated by modelling the spatial autocorrelation expressed in the structure function. The experimental structure function cannot be used directly in the calculation of the weights w_i, since it represents a discrete estimate of the spatial autocorrelation. Consequently, the estimation is based on experimental variograms, quantities describing the spatial continuity. Between the several variograms a spherical variogram is used, as in other flows interpolations proposed in literature (i.e Castiglioni et al., 2008).
With a jackknife procedure, described above, the RMSE is calculated for the three proposed subdivisions and for both the proposed low flow indices (Tab. 3.9).

Table 3.9 Values of the RMSE - Root Mean Square Error for Ordinary Kriging interpolations.

Subdivision	Regions	RMSE Q(7,2)	RMSE Q70
Unique	Unique	3.02	8.65
3 regions	North	3.89	11.33
	Centre	2.60	3.42
	South	0.74	2.08
5 regions	North East	3.94	10.69
	North West	3.82	11.06
	Centre East	0.58	0.51
	Centre West	0.61	1.01
	South	0.69	1.84
	Mean	2.54	7.23

Results are really similar to the one found with the IDW even if there is an improving of results especially for the northern regions. Results confirm the good properties of homogeneity of the final subdivision for three sub-regions (South, Centre East, Centre West) while for other two (North East and North West) the results are not the expected ones, even if less biased than the ones found with the IDW interpolation.

3.4.10 Multivariate modelling of low flow indices

The multivariate estimation is a relationship between dependent low-flow characteristics and independent catchment and climatic variables. To establish a usable regression relationship, a certain amount of observed streamflow data should be available to adequately represent the variability of flow regimes in a region and to allow required low-flow characteristics (dependent variables) to be estimated for further use in regression analysis. The streamflow data used should represent natural flow conditions in the catchments: the approach will most probably not work or will be misleading if flow regimes analysed are continually changing under man-induced impacts.

Technically, regression model is constructed by means of a multiple regression analysis. This step includes selection of type of regression model, estimation of regression model parameters, assessment of estimation errors.

It is not an easy task to uncover a true physical relationship between dependent and independent variables without some prior knowledge of which basin characteristics should be included in the regression equation. However, in some cases the world-wide or local experience may suggest the required set of independent physiographic variables. Vogel and Kroll (1992) adapted the conceptual catchment model to identify primary low-flow generating factors and found that low-flow characteristics are highly correlated with catchment area, average basin slope, and base flow recession constant, with the base flow recession constant acting as a surrogate for both basin hydraulic conductivity and soil porosity. It was concluded that a simple physically based catchment model could suggest variables and the functional form for regional regression equations that estimate low-flow statistics at ungauged sites. However, Nathan and McMahon (1976) explicitly stated that regression models "…are in effect a black-box solution to the problem… where only inputs and outputs have any real significance". The chosen regression model is a linear combination of the physiographic and climatic catchment characteristics.

Basin and climate characteristics (independent variables) which are most commonly related to low flow indices include: catchment area, mean annual precipitation, channel and catchment slope, stream density, percentage of lakes and forested areas, various soil and geology indices, length of the main stream, catchment shape and watershed perimeter, mean catchment elevation (Smakhtin, 2001). After some preliminary elaborations, it seemed rather important to include in the model the sample averages of mean rainfall time series. All the characteristics are estimated through a procedure with the software ArcGis and its Spatial Analyst and Arc Hydro tools.

Arc Hydro tools are used to derive several data sets that collectively describe the drainage patterns of a catchment. Raster analysis is performed to generate data on flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation. These data are then used to develop a vector representation of catchments and drainage lines. Using this information, a geometric network is constructed.

Arc Hydro needs terrain data to work. A Digital Elevation Model (DEM) of the area is added (Fig. 3.13). The DEM is downloaded by internet. It is part of the world DEM created within the project SRTM 3 (Version 2). The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) for over 80% of the globe. This datum is currently distributed free of charge by USGS and is available for download from the National Map Seamless Data Distribution System, or the USGS ftp site. SRTM datasets result from a collaborative effort by NASA and NGA, as well as the participation of the German and Italian space agencies to generate a near-global digital elevation model of the Earth using radar interferometry. The SRTM datasets cover all the continental landmasses, except the Polar Regions. Moreover it has some mountain and desert no data (void) areas. Sometimes referred to as "90 meter" data, the sample spacing of SRTM3 for individual data points is 3 arc-seconds. Version 2 of the SRTM digital topographic data (also known as the finished version) is the result of a substantial editing effort by the NGA and exhibits well-defined water bodies and coastlines and the absence of spikes and wells (single pixel errors), although some areas of missing data are still present. The SRTM data is available as 3 arc second DEMs. The vertical error of the DEM's is reported to be less than 16m.

It is downloaded in WGS84 – UTM geographic coordinate system. This projection became the basis for the entire project. The obtained DEM is reduced in order to have the coverage of the considered area but without having a too big grid. In this way the time of the successive elaborations is reduced. This DEM has a mean spatial resolution of 70 m.

In Arc Hydro a DEM pre-processing is required before the delineation of watersheds. Terrain Pre-processing uses DEM to identify the surface drainage pattern. Once pre-processed, the DEM and its derivatives can be used for efficient watershed delineation and stream network generation. Terrain Pre-processing has several steps that should be performed in sequential order, from top to bottom. All of the pre-processing steps from Flow Direction down to Adjoint Catchment Processing must be completed before Watershed Processing functions can be used. DEM reconditioning, Build Walls and Fill Sinks might not be required, depending on the quality of the initial DEM.

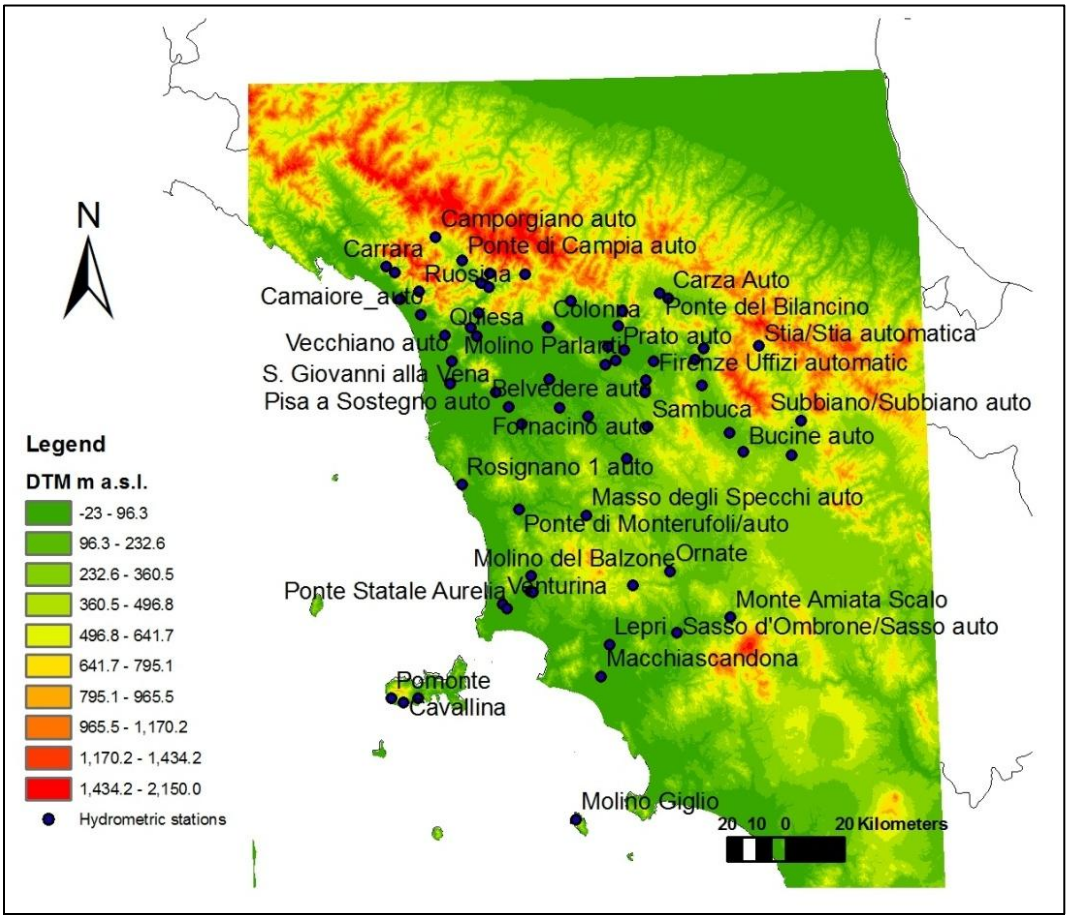


Figure 3.13 Obtained Digital Elevation Model - DEM.

The terrain pre-processing starts with the Level DEM function. This function modifies a DEM by setting the cells within the selected Lake Polygon features to the associated value. The function works on a selected set of polygon features or on all features if there is no selected set. Lakes characteristics are taken into account through a shapefile produced by Region Tuscany – Sportello Cartografico (Cartographic Sector). The terrain pre-processing continues with the DEM Reconditioning. This function modifies a DEM by imposing linear features onto it (burning/fencing). It is an implementation that permits to solve problems in areas that have a heavy anthropogenic impact. This application is very useful in drainage areas like Val di Chiana, Piana Fiorentina, Pianura Pistoiese, Pianura Pisana, and Maremma in which the entire hydraulic network is artificial. The function needs as input a raw DEM and a linear shapefiles (i.e. river to burn in) that both have to be present in the map document. The river channel main network, insert in a shapefile created for previous studies, is dropped of 20 m. This is a high value, but it is the only one that permits to simulate the flow direction in drainage areas. Another function utilized in this work is the Wall building function. This function allows "building" walls in the input grid. Two types of walls may be created:

- Outer walls – based on an input polygon feature class (Outer Wall Polygon).
- Inner walls – based on an input polygon, line or point feature class (Inner Wall Feature).

The first walls are created to subdivide the Arno River and the Tevere River catchments in Val di Chiana Area. This subdivision is artificial, since that, till the II century a.D. the Chiana River flowed into the Tevere River and not into the Arno River.
The Sink prescreening function allows prescreening the potential sinks in the input Raw DEM by filling the pits with a drainage area smaller than the specified area threshold defining a potential sink. Sink Prescreening is useful to reduce the number of potential sinks processed by the function Sink Evaluation. The minimum drainage area for a pit to be considered a potential sink is 1 km^2, the minimum surface that a considered lake should have.
The Sink Evaluation function allows generating the Sink Polygon and Sink Drainage Area feature classes for the input DEM as well as characterizing the sink features. The Sink Selection function allows selecting the Deranged Polygon features (i.e. sinks) that should be considered as sinks. The function works on a selected set of features or on all features if there is no selected set.
The Fill Sinks function fills the sinks in a grid. If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.

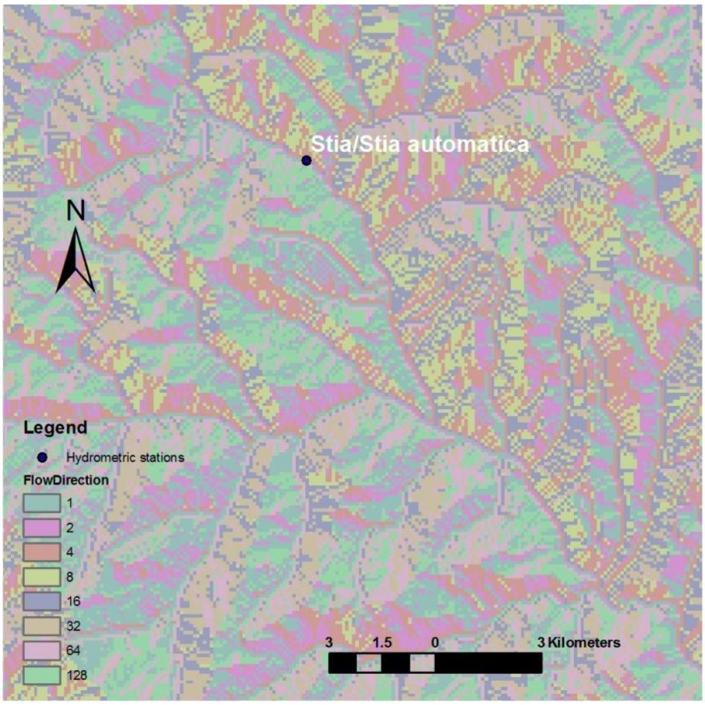


Figure 3.14 Flow Direction raster of "Casentino" area in the upper part of Arno River basin obtained with Arc Hydro.

The Flow Direction Function computes the flow direction for a given grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell (Fig. 3.14).
The Flow Accumulation function computes the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

Once that Flow Direction and Flow accumulation are performed, it is possible to use the Stream Definition function. This function computes a stream grid containing a value of "1" for all the cells in the input flow accumulation grid that have a value greater than the given threshold. All the other cells in the Stream Grid contain no data. These streams are used to prepare pre-processed data that will help to speed up point delineation. These streams do not need to be meaningful or representative of existing streams. The default value is utilized for the river threshold. This value represents 1% of the maximum flow accumulation: it is the recommended threshold for stream determination.
Stream Segmentation function creates a grid of stream segments that have a unique identification. Either a segment may be a head segment, or it may be defined as a segment between two segment junctions. All the cells in a particular segment have the same grid code that is specific to that segment. The input Sink Watershed Grid and Sink Link Grid are optional and may be used to mask the input stream grid so that no stream links are created in those areas.
Combine Stream Link and Sink Link function creates a link grid combining the stream link grid representing dendritic areas and the sink link grid representing deranged areas (i.e. areas with sinks).
Catchment Grid Delineation function creates a grid in which each cell carries a value indicating to which catchment the cell belongs. The value corresponds to the value carried by the stream segment or sink link that drains that area, defined in the input stream segment link grid (Stream Segmentation) or sink link grid (Sink Segmentation). Catchment grids are converted into a catchment polygon feature with the Catchment Polygon Processing function.
At this point Drainage Line Processing function can be performed. This function converts the input Stream Link grid into a Drainage Line feature class. Each line in the feature class carries the identifier of the catchment in which it resides. Then the Adjoint Catchment Processing generates the aggregated upstream catchments from the Catchment feature class. For each catchment that is not a head catchment, a polygon representing the whole upstream area draining to its inlet point is constructed and stored in a feature class that has an Adjoint Catchment tag. This feature class is used to speed up the point delineation process. Longest Flow Path for Catchments function is then performed. It allows generating the longest flow paths associated to the catchments. This is required to speed up the generation of Longest Flow Paths. Several functions (Slope, Slope greater than 30, Slope greater than 30 and facing North) allows generating and managing a slope grid in percentage for a given DEM.
Once the terrain pre-processing is performed, the Watershed Processing is carried out. With the function Batch Subwatershed Delineation sub-watersheds are delineated for all the considered hydrometric stations that are digitalized with their UTM coordinates (Fig. 3.15).

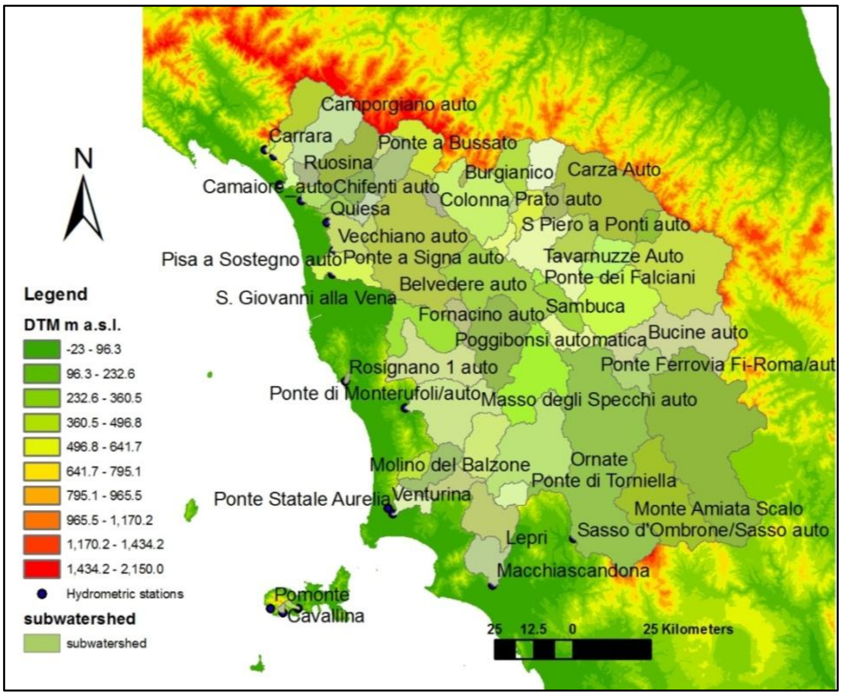


Figure 3.15 Sub watersheds determined for each hydrometric station with Arc Hydro tools.

With Longest Flow Path for Subwatersheds function the longest flow path for input sub-watersheds is found.
With these data it is possible to characterize each sub-watershed with:

- longest flow paths (*FP*): in km, calculated with the function described above; it is used as geomorphoclimatic characteristic in Tucci et al. (1995) and Pyrce (2004);
- topographic mean slope (*Sl*): in percentage, a slope grid is calculated with the function described above, then the values are averaged for each sub-watershed with the Zonal tool of Spatial Analysis Toolbox; it is used as geomorphoclimatic characteristic in Castellarin et al. (2004), Chokmani and Ouarda (2004), and Laaha and Bloeschl (2006);
- mean elevation a.s.l. (*Hmean*): in m, the values are averaged for each sub-watershed with the Zonal tool of Spatial Analysis Toolbox; it is used as geomorphoclimatic characteristic in Gottshalck (1985), Castellarin et al. (2004), Pyrce (2004), Laaha and Bloeschl (2006), Castiglioni et al. (2008), and Viglione et al. (2006);
- difference between the maximum and the minimum high (ΔH): in m, the values are calculated for each sub-watershed with the Zonal tool of Spatial Analysis Toolbox; it is used as geomorphoclimatic characteristic in Castellarin et al. (2004), Laaha and Bloeschl (2006), and Viglione et al. (2006);
- mean value of Mean Annual Precipitation (*MAP*): in mm, the values are averaged for each sub-watershed with the Zonal tool of Spatial Analysis Toolbox starting from a MAP grid calculated in previous studies (Caporali et al., 2008) (Fig. 3.16); it is used as geomorphoclimatic characteristic in Castellarin

et al. (2004), Pyrce (2004), Chokmani and Ouarda (2004), Laaha and Bloeschl (2006), Castiglioni et al. (2008), and Viglione et al. (2006);

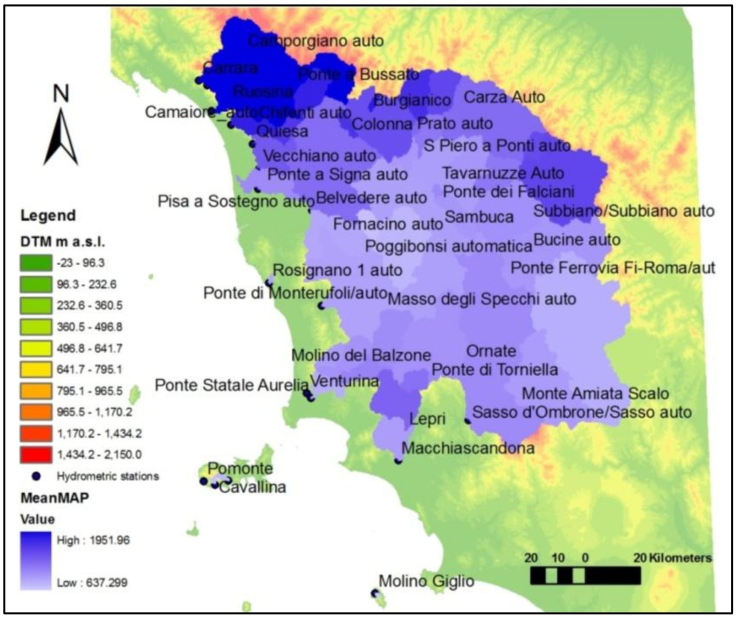


Figure 3.16 Sub-watersheds Mean Annual Precipitation - MAP.

- mean soil permeability (*SP*): in percentage, it is calculated as in other studies (Santhi el al, 2008, Castiglioni et al., 2008) as the percentage of sand into the first 50 cm of the soil. This information is obtained from a soil map shapefile downloaded by Region Tuscany - Cartographic Sector website (Fig. 3.17). It is used as geomorphoclimatic characteristic in the mentioned studies.

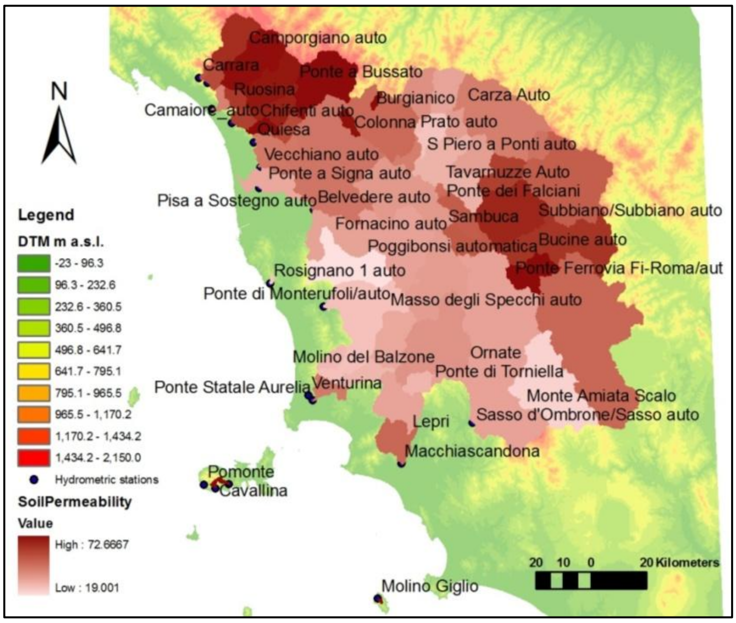


Figure 3.17 Sub-watersheds soil permeability from the percentage of sand.

All the characteristics for the sub-watersheds of the considered hydrometric stations are summarized in Tab. 3.10.

Table 3.10 Sub-watersheds geomorphoclimatic characteristics.

Code	Q(7,2)/A	Q70/A	Flow Legth	Mean Slope	Mean MAP	MEAN H	Δ H	soil permeab
	l/s/km²	l/s/km²	km	%	mm	m	m	%
4005	5.37	6.241	5.37	4.97	1537.3	735	1275	38.60
4010/4011	9.90	18.739	9.92	6.05	1799.8	768	1744	39.82
4017	27.46	12.474	9.54	5.41	1952.0	660	1699	42.47
4045	8.16	14.626	16.94	4.95	1790.31	551	1808	37.76
4059	0.57	4.178	14.47	3.49	1428.4	392	1265	41.48
4115	2.00	5.144	19.75	3.42	1585.7	1040	1656	44.19
4165	0.77	1.239	29.50	3.75	1695.68	942	1844	46.93
4195	3.49	4.697	42.35	3.79	1694.92	856	1924	47.16
4200	8.59	16.414	11.69	4.80	1641.8	1045	1603	48.88
4231	10.46	35.195	23.68	3.47	1791.0	1036	1572	55.30
4255	0.84	1.726	41.34	3.76	1614.22	886	1796	52.67
4284	2.23	3.596	59.11	3.78	1658.92	825	1987	48.61
4286	3.97	4.959	15.32	2.00	1300.2	206	975	39.91
4291	3.99	7.131	69.36	3.66	1635.34	779	2002	48.35
4365	16.00	20.211	79.32	3.42	1576.78	704	2036	46.58
4379/4380	1.84	5.274	13.06	2.75	1192.6	892	1159	33.65
4410/4411	1.31	4.106	48.28	2.46	1225.34	754	1369	36.58
4520/4521	0.18	0.519	92.83	1.47	428.58	264	1395	12.79
4568	0.12	0.691	31.48	1.58	844.8	380	642	52.26
4571	0.37	0.723	112.84	1.47	902.04	454	1496	38.01
4591	0.58	1.082	133.18	1.53	899.21	451	1521	38.97
4610	0.51	2.664	18.74	1.96	1227.8	479	894	26.72
4623	1.87	2.880	17.24	2.26	1042.1	459	703	27.76
4640/4641	1.05	3.600	60.30	2.33	1081.27	490	1548	30.60
4659/4660	0.76	2.241	142.80	1.70	937.95	458	1556	37.43
4679	0.14	1.887	158.30	1.70	935.14	451	1588	37.08
4710	0.10	0.692	29.60	1.66	852.4	346	777	37.03
4723	0.03	0.859	35.25	1.64	860.09	326	1198	36.71
4779/4780	2.17	5.667	30.52	3.19	1338.3	567	1149	29.47
4782	9.54	4.613	36.30	3.13	1311.76	541	1198	28.88
4791	0.54	2.239	46.57	2.74	1194.51	448	1226	26.61
4811	1.09	1.864	173.16	1.82	991.30	454	1623	37.69
4860	1.08	3.692	8.36	2.57	1435.6	455	1027	54.22
4875	1.96	4.936	37.01	1.56	1191.40	249	1142	35.65
4901	1.92	2.835	180.46	1.71	958.07	412	1624	35.67

continued

Code	Q(7,2)/A	Q70/A	Flow Legth	Mean Slope	Mean MAP	MEAN H	Δ H	soil permeab
	l/s/km²	l/s/km²	km	%	mm	m	m	%
4910	0.17	1.034	27.33	1.84	823.7	448	715	37.61
4965	4.84	6.178	34.74	1.14	807.5	284	575	27.77
4970	2.09	2.790	46.94	1.23	768.67	247	613	27.35
5001	1.42	2.024	194.68	1.61	924.24	375	1624	34.24
5005	0.54	0.326	19.14	1.38	692.6	181	500	27.05
5040	0.00	1.231	13.75	2.53	1318.0	364	859	48.27
5050	6.79	37.037	3.13	1.63	1221.3	182	128	48.27
5130/5131	0.14	0.623	43.57	1.37	799.4	234	637	19.00
5161	1.61	2.210	63.24	1.28	797.32	188	651	22.54
5190	0.73	2.013	216.30	1.54	928.28	335	1628	33.33
5231	11.20	14.462	240.83	1.53	927.92	331	1631	33.21
5345	337.13	62.592	4.72	1.18	789.5	127	305	22.37
5372	0.06	0.294	29.97	1.90	886.4	464	907	26.29
5400/5401	0.05	0.353	43.03	1.64	832.99	324	1019	24.26
5460	0.00	0.310	11.95	1.52	837.8	224	482	24.11
5470/5471	0.04	0.385	27.11	1.41	801.40	247	794	21.89
5485	0.00	0.050	29.89	1.64	937.5	348	850	24.18
5510	0.00	0.000	47.15	2.49	677.62	191	901	21.90
5601	0.21	0.527	45.69	1.19	976.09	169	906	30.14
5610	1.24	2.786	33.11	1.29	1079.7	226	924	26.64
5710	5.11	4.035	59.557	1.36	873.3	367	896	28.89
5720	0.30	0.829	16.219	1.62	1012.9	474	458	24.72
5760	0.11	0.431	43.197	1.28	836.2	417	967	20.87
5790/5791	0.56	1.370	104.36	1.32	884.76	354	1659	26.02
5940	0.19	1.346	3.94	3.64	684.8	415	840	72.67
5950	0.00	0.448	6.20	2.46	711.5	300	882	65.66
5960	0.43	0.435	2.84	2.68	637.3	254	471	72.67

The regionalisation approach requires the development of a regional predictive model for Q70 and Q(7,2). To this aim, the natural logarithms of all geomorphoclimatic characteristics for the 63 sites were regressed against the corresponding Q70 and Q(7,2) values trough a least square mean error procedure. The linear model, used for its simplicity and for the good results it is able to give (Laaha and Bloeschl, 2006), has the form:

$$\begin{aligned} Q^* = a_1 + a_2 \ln(FP) + a_3 \ln(Sl) + a_4 \ln(Hmean) + a_5 \ln(\Delta H) + \\ + a_6 \ln(MAP) + a_7 \ln(SP) \end{aligned} \tag{3.26}$$

where Q^* is either Q70 or Q(7,2); *FP, SL, Hmean, ΔH, MAP* and *SP* are the explanatory variables of the model, the suitable set of geomorphic and climatic indices; a_i, for i = 0, 1,... , 7, are parameters. The optimal subset of explanatory variables and the estimates of a_i, with i = 0, 1,... , n for both the indices were identified through a least square mean

error procedure. Logarithms allow to have variables values easier to be compared (Castellarin et al., 2004) and to have coefficients with the same order of magnitude.
The procedure is applied to the whole region and then to the two subdivisions tested before for the Q(7,2) as well as for the Q70. In Tab. 3.11 are summarized the values of the parameters for the different cases. In some subdivisions the equations are reduced eliminating some parameters that show a little correlation with the calculated index.
Therefore, for example, for the sub-region North East in the subdivision into 5 regions the relation for the Q(7,2) is:

$$\begin{aligned} Q(7,2) = &-26.84 - 3.66\ln(FP) + 3.07\ln(Sl) + 7.04\ln(Hmean) + \\ &- 3.50\ln(\Delta H) - 4.72\ln(MAP) + 4.93\ln(SP) \end{aligned} \tag{3.26}$$

While for the sub-region South in the subdivision into 5 regions the relation for the Q70 is:

$$Q70 = -17.07 + 0.65\ln(FP) - 3.88\ln(Sl) - 0.27\ln(Hmean) + 2.66\ln(\Delta H) \tag{3.27}$$

with FP in km, Sl in %, $Hmean$ in m, ΔH in m, MAP in mm, SP in %.

Table 3.11 Parameters of the considered multivariate model.

Index	Subdivision	Sub-region	a_1	a_2	a_3	a_4	a_5	a_6	a_7
Q(7,2)	Unique		-2.02	-5.48	-7.50	10.96	-7.34	1.27	-1.88
Q(7,2)	3 regions	Nord	-19.66	1.64	3.77	4.04		-3.05	1.90
Q(7,2)	3 regions	Centre	-17.80		0.85	2.77	-0.40	0.18	
Q(7,2)	3 regions	South	-5.44	0.13	1.19	0.12	0.69		
Q(7,2)	5 regions	North East	-26.84	3.66	3.07	7.04	-3.50	-4.72	4.93
Q(7,2)	5 regions	North West	-32.27	-3.15	0.98	5.05		-0.58	3.40
Q(7,2)	5 regions	Centre East	6.56	0.60	2.28	0.37		-1.07	-1.32
Q(7,2)	5 regions	Centre West	-21.57		2.33	3.96	-1.91	0.89	-0.38
Q(7,2)	5 regions	South	-5.14	0.19	1.48	0.09	0.60		
Q70	Unique		-19.01	-0.07	1.73	17.85	-4.16	-7.67	-0.63
Q70	3 regions	Nord	-12.53	7.09	7.33	30.67		-20.09	6.99
Q70	3 regions	Centre	-44.56		2.67	6.58	-1.12	0.90	
Q70	3 regions	South	-17.78	0.50	3.22	-0.18	2.85		
Q70	5 regions	North East	-22.34	11.34	-3.60	47.20	-0.08	-25.10	8.45
Q70	5 regions	North West	-80.38	-0.47	0.85	16.21		-6.81	3.14
Q70	5 regions	Centre East	-33.21	0.45	5.57	4.06		-0.05	0.68
Q70	5 regions	Centre West	-40.86		7.41	8.65	-5.35	2.26	-1.62
Q70	5 regions	South	-17.07	0.65	3.88	-0.27	2.66		

The models were than validated through the calculation of the RMSE. It is calculated for the three proposed subdivisions and for both the proposed low flow indices (Tab. 3.12). Results for the Multivariate Analysis confirm the ones found with the IDW and the Ordinary Kriging. There is an improving of results especially for the northern regions in the subdivision into 5 regions. Results confirm the good properties of homogeneity of the final subdivision into 5 regions.

Table 3.12 Values of the RMSE - Root Mean Square Error for Multivariate Analysis.

Subdivision	Regions	RMSE Q(7,2)	RMSE Q70
Unique	Unique	9.07	7.80
3 regions	North	3.34	7.41
	Centre	0.35	0.50
	South	0.18	0.39
5 regions	North East	2.25	2.96
	North West	1.26	0.99
	Centre East	0.32	0.13
	Centre West	0.12	0.31
	South	0.18	0.39
	Mean	1.25	1.53

3.4.11 Comparison between low flow indices estimation methods

Low flow considered indices, Q(7,2) and Q70, are estimated for each sub-region. Two interpolation techniques, Inverse Distance Weighted and Kriging, are applied. The results are valuated using the jackknife method. Even a Multivariate Analysis is carried out, choosing an appropriate set of geomorphoclimatic characteristics. The root mean square error is assessed to compare the results, to quantify the accuracy of the different techniques and to define the most suitable procedure for low flow regionalisation. Estimation methods confirm the goodness of the final subdivision into five sub-regions.

Table 3.13 Considered estimation methods: comparison between the RMSE for the final subdivision into 5 regions (mean RMSE is in **bold**).

Estimation method	Regions	RMSE Q(7,2)	RMSE Q70
IDW	North East	4.14	15.20
	North West	4.10	10.76
	Centre East	0.58	0.64
	Centre West	0.63	0.86
	South	0.70	2.08
	Mean	**2.76**	**8.96**
Ordinary Kriging	North East	3.94	10.69
	North West	3.82	11.06
	Centre East	0.58	0.51
	Centre West	0.61	1.01
	South	0.69	1.84
	Mean	**2.54**	**7.23**
Multivariate Analysis	North East	2.25	2.96
	North West	1.26	0.99
	Centre East	0.32	0.13
	Centre West	0.12	0.31
	South	0.18	0.39
	Mean	**1.25**	**1.53**

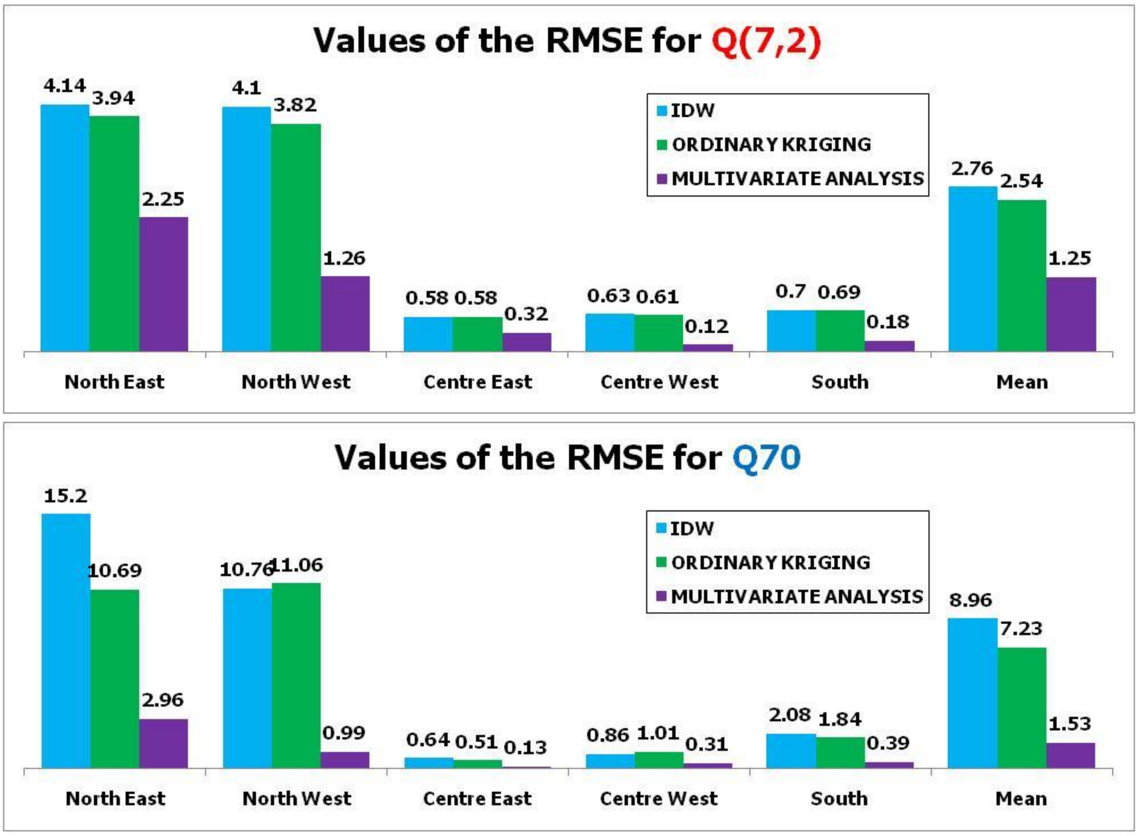


Figure 3.18: RMSE values for Q(7,2) (above) and Q70 (below) for the subdivision in 5 regions in the three considered interpolation techniques.

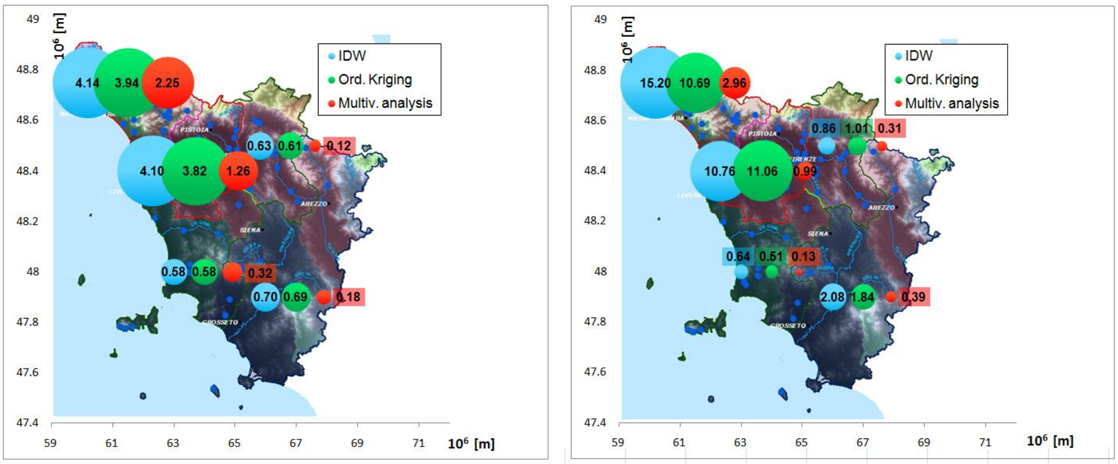


Figure 3.19: RMSE values for Q(7,2) (left) and Q70 (right) for the subdivision in 5 regions in the three considered interpolation techniques. The circumferences ray is proportional to the RMSE.

The RMSE for the different estimation methods for the final subdivision into five sub-regions is reported in Tab. 3.13 and shown in figures 3.18 and 3.19. Inverse Distance Weighted is the estimation methods that perform worse. Ordinary Kriging performs better, especially in the North East and North West sub-regions, but the results are still worst than expected. The Multivariate Analysis is the estimation method that performs best. It is able to solve the problems in the two northern regions, which still have the highest RMSE values, but evidently smallest than with the previous techniques. In these last two regions the considered low flows indices present a high variability that can be explained taking into account the geomorphoclimatic characteristics (Fig. 3.20).

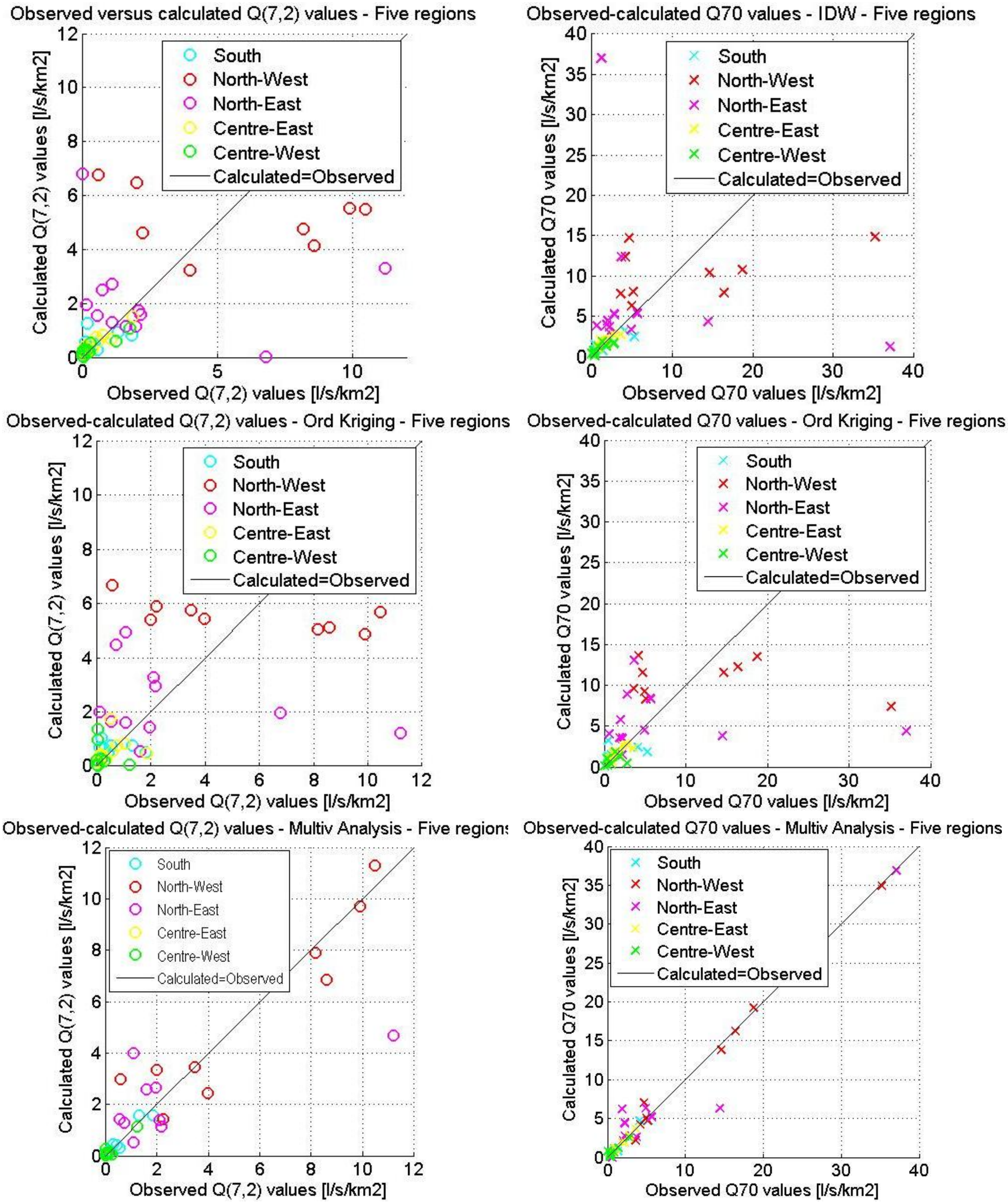


Figure 3.20 Considered estimation methods: comparison between observed and calculated values for the final subdivision into 5 regions; IDW (above), Ordinary Kriging (centre) and Multivariate Analysis (below).

CHAPTER 4 – A PROCEDURE FOR DROUGHT RISK ASSESSMENT

4.1 INTRODUCTION

Prolonged absence of precipitation, soil moisture deficit and decreasing in river flows do not necessarily mean scarcity in an artificial water resources system, because water can also be supplied from natural or artificial reservoirs: snow pack, aquifers, and regulation dams can sustain water demands during periods of meteorological drought. If drought conditions persist, reservoirs in the system are depleted of their reserves, and a period of water scarcity could start (Rossi, 2000). Droughts always start as a meteorological phenomenon with persistent precipitation deficiencies over a region. After a while, these deficiencies deplete soil moisture content and produce impacts on natural and rainfed agricultural systems, which have only a limited capacity to store water in the soil. The river basin has more mechanisms to buffer droughts, mainly through storage of groundwater in aquifers, but if the drought persists, the effects are also seen in hydrological systems. Low water tables and reduced river flows, which affect river ecosystems and riparian zones are the mainly shown of hydrological drought. Natural systems have developed a variety of methods to cope with droughts, and are usually able to survive under strong water shortages and to recover after the drought is over (Martin Carrasco and Garrote, 2007). In human systems droughts lead to water shortages and to economical, environmental and common health deteriorations. Shortages risk depends even on demand fluctuation and on the actions carried out in order to reduce drought effects. For those reasons, dynamic indicators, relating resources and demand, are required in order to identify the probability of occurrence of situations with a certain risk of water shortages (Garrote et al., 2008).

In large systems, powerful instruments with mathematical simulation may be used to obtain quantitative results accounting for all system complexities in an uncertain context (Labadie, 04). In fact, many factors, such as the stochastic nature of inflows, the presence of different conflicting demands changing over time, the high level of complexity of the system or the interactions among the different components, mitigation measures and uncertainty related to the actual impacts of extreme events, make the risk assessment of a water supply system associated to drought a problem that is difficult to solve. The simulation models provide guidance for identifying unsatisfied demands, evaluating the effect of yield enhancement or water conservation measures, and scheduling available actions. All models provide a measure of demand reliability, quantified as the probability that a given demand may suffer water shortages during a given time horizon (Alecci et al., 1986).

Water resources system models provide additional information which usually does not reach decision makers because of its highly complex and technical nature. The system modeller could easily determine if the lack of reliability in any given demand should be corrected with supply enhancement measures, new or expanded infrastructure for

water regulation or transport, or demand management, but conveying this information to decision makers is usually a challenging task (Grigg, 1996). Furthermore, as water management issues become increasingly controversial due to rising marginal costs of infrastructure and reinforced environmental awareness, public participation in the decision-making process becomes more important. This increasing tendency of public participation in water related issues requires that results of technical analysis would be presented in a way that can be understood and shared by all stakeholders, including those with little technical background. The process of plan discussion and negotiation is very important, since consensus is a major goal to achieve before the plan is operational. It is important that the rationale behind the measures proposed in the plan can be understood by all stakeholders that might be affected by them, and therefore, special emphasis has been placed on developing simple indices to summarize and transfer the results to the non experts. Quantitative indices simplify information transfer from staff experts to decision makers because they account for complex interrelationships among many factors in just a few key values. Indices will also allow for objective comparisons of different systems and, therefore, are useful tools to classify systems and establish priorities (Martin Carrasco and Garrote, 2007).
An analysis of the relationship between the risk of failure of water supply systems and the available water stored in reservoirs is proposed in this work (Fig. 4.1). In particular, operating rules for drought mitigation are developed defining some threshold values, expressed in probabilistic terms. The ones that perform best are chosen with an optimization process. A simplified model of the water resources system is settled up. The threshold values are validated with Monte Carlo simulations and the operating rules with long term simulations, both performed with the software WEAP. The critical situations are assessed month by month in order to evaluate optimal management rules during the year and avoid conditions of total water shortage. The methodology is applied to the urban area of Firenze in central Tuscany, in central Italy.

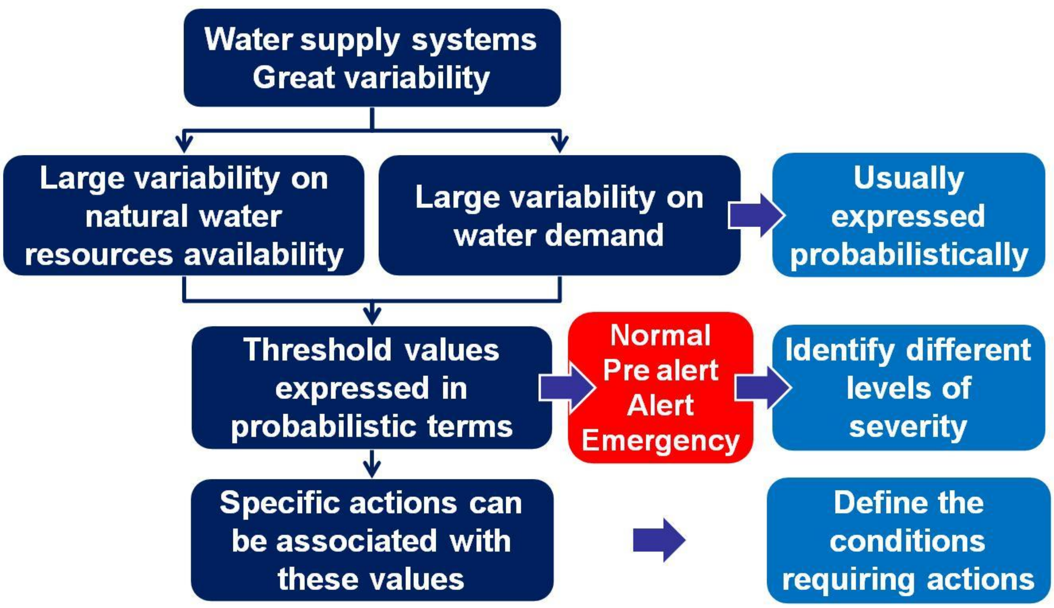


Figure 4.1 Drought risk assessment: methodological approach flow chart.

4.2 LONG TERM AND SHORT TERM RISK ASSESSMENTS

Following the risk management framework, risk analysis can be divided into risk identification, risk assessment and risk treatment and management (Pliefke et al., 2007). The first one is the condition of being aware of a dangerous situation. The second one is oriented to the estimation of the probabilistic features of a hazard, whereas the third one is generally defined as a pro active approach for coping with risk through planned actions that mitigate the effects of the adverse phenomenon.

Several classifications of drought risk assessment and drought risk management activities are available in the literature. With respect to drought risk assessment, depending on the time span of the analysis, on the probabilistic approach and even on the considered mitigation measures, drought risk estimations can be subdivided into long term and short term risk assessments. Long term activities, that use a long time horizon (30-40 years), are oriented to evaluate the adequacy of the system in order to improve its reliability to meet future water demands. One of the primary objective of long term analysis is evaluating the system state variables and other variables related to the satisfaction of various demands (e.g. water supply shortages) under a given system configuration and a given set of operating rules by considering, as hydrological input, several generated streamflow series. Furthermore, a similar assessment is also required for the satisfaction of ecological requirements, such as stream flow requirements, and for target storages in reservoirs. Monte Carlo simulations are needed in order to evaluate the system with a long term simulation. Monte Carlo methods (or Monte Carlo approaches) are a class of computational algorithms that rely on repeated random sampling to compute their results. Monte Carlo methods are often used in simulating physical, mathematical and statistical systems. Because of their reliance on repeated computation of random or pseudo-random numbers, these methods are most suited to calculation by a computer and tend to be used when it is infeasible or impossible to compute an exact result with a deterministic algorithm.

Monte Carlo simulation methods are especially useful in studying systems with a large number of coupled degrees of freedom. More broadly, Monte Carlo methods are useful for modelling phenomena with significant uncertainty in inputs, such as the calculation of risk in drought management. These methods are also widely used in mathematics: a classic use is for the evaluation of definite integrals, particularly multidimensional integrals with complicated boundary conditions. It is a widely successful method in risk analysis when compared with alternative methods or human intuition (Hammersley and Handscomb, 1975).

The term "Monte Carlo method" was used for the first time in the 1940s by physicists working on nuclear weapon projects in the Los Alamos national laboratory in the United States of America, after the famous Monte Carlo casino. It is a gambling instrument based on random number generation (Metropolis, 1987). Enrico Fermi in the 1930s and Stanisław Ulam in 1946 are the first ones that had this idea (Metropolis and Ulam, 1949).

There is no single Monte Carlo method; instead, the term describes a large and widely used class of approaches. However, these approaches tend to follow a particular pattern:

- to define a domain of possible inputs;
- to generate inputs randomly from the domain using a certain specified law;
- to perform a deterministic computation using the inputs;
- to aggregate the results of the individual computations into the final result (Hammersley and Handscomb, 1975).

For the problem object of this study inputs to perform a Monte Carlo Simulation can be obtained mainly with two techniques. The first one is to produce a number of inflow series using different periods of registration of the input variables. To perform this approach long periods of streamflow series are needed. Since that long recorded are usually not available, a second techniques, creating synthetically generated series is carried out. Synthetically generated series can be obtained by means of a stochastic model fitted to the observed series, such that the generated series resemble, in a statistical sense, the observed ones. Thus, each generated series can be considered as one of the possible series that will occur in the future and, as a consequence, the data resulting can be seen as a large sample from the population of all the possible system behaviours in the future. Then, probabilistic features of the consequences of drought can be assessed by performing a statistical analysis of the results of simulation.
Short term procedure makes use of the same basic tools, but the analysis is performed with reference to a shorter time horizon (2-3 years) and by taking into account the initial conditions of the system. Short term actions evaluate the operating rules, the management measures and their capability to reduce the most negative impacts of severe droughts. Different criteria could be applied to decide the length of time horizon for conditional risk assessment of a given system. In particular it should be defined taking into account the length of historic droughts, the consolidated operating procedure of the system, and the time horizon prescript by the law, the need to avoid the growth of evaporation losses caused by a multiannual management of reservoirs (Cancelliere et al. 1998).
In addition to this main classification of risk assessment, other categorizations are present in literature. In the long term risk assessment the evaluation is generally unconditional, without taking into account the initial conditions of the system. In the short term risk assessment the evaluation is conditional, since the initial state of the system is evaluated as the actual situation at the moment of the simulation.
With respect to drought risk management, several actions have been proposed to mitigate drought risk and they span from economic incentives for water savings, to the constructions of new infrastructures, from insurance programmes to restriction of irrigation, from use of additional sources of low quality to techniques to reduce crops water consumption. Two different approaches to drought phenomenon are distinguished: the reactive and the proactive one. The reactive measures are defined as those that are essentially implemented once visible impacts are already in progress and a drought occurs. The proactive (or preventive) measures are defined as those,

conceived or prepared in advance, which may help in the alleviation of drought consequences (Rossi, 2007). Following the long term and short term risk assessment, the mitigation measures have been defined respectively as long term and short term actions or as strategic planning and tactical responses to the drought (Werick, 1993). A consolidated classification of drought mitigation measures has been proposed (Yevjevich et al., 1978), distinguishing three categories of measures: the first ones to increase water supply, the second ones to reduce water demands and the last ones to minimize drought impacts. In this work a mixed procedure is used. Long term simulations are performed considering different amount of water present in the system in the first year. The approach is consequently conditional and it will lead to a proactive approach with a strategic planning containing mitigation measures that have the main goal to reduce water demands.

4.3 DROUGHT INDICATORS

There are several approaches that try to define the probability of shortages of a selected system, but there is no general agreement about them. Most of the studies used indicators whose values are related to the probability water shortages. The basis of any drought management plan is a robust system of indicators that can identify and diagnose anomalies in water availability and can provide the basis for early detection of drought episodes (Gustard et al., 2004). Variables used as early warning levels to predict droughts are grouped in two categories: informative and operational. Informative variables provide information on the development of the drought, and are used as a monitoring tool. Executive variables are objective indicators that are used to trigger specific actions in an operational context (Fisher and Palmer, 1997). Generally, hydrologic indicators used to define triggers are physical measures of a system, such as reservoir storage, streamflow levels, or groundwater supply. Reservoir storage is useful because it is relatively easy to determine. In the drought management plan, the monitoring system should be linked to specific actions through one or more indicators that can be used as triggers of drought mitigation measures (Garrote el al., 2007). Use of triggers for drought management requires comparing a forecast of supply and demand. If a water supply has few stresses (i.e. supply exceeds demands or drought events are very infrequent), little management is needed to prepare or respond to water shortages. In this case, simple indicators, such as reservoir storage or cumulative precipitation, compared to 'normal' may be adequate (Fisher and Palmer, 1997).

For these reasons levels into the reservoir are used as drought indicator. It has been selected as operational variable and it has been used as thresholds to trigger specific actions. In this work the relationship between water crisis and failure of water supply systems and reservoirs volumes is analysed. The threshold values are defined considering the probability to satisfy a given fraction of the demand in a certain time horizon and the risk of shortages is represented by volume in reservoir – deficit/risk curves.

The operational effectiveness of the drought management plan is greatly enhanced if the selected measures for every system are grouped in packets, which are applied if certain conditions are met. In this work drought management strategies are grouped in four scenarios, corresponding to increasing levels of severity: normal, pre-alert, alert, and emergency scenarios.

4.4 USE OF A DECISION SUPPORT SYSTEM

4.4.1 Introduction

Under water scarcity conditions, simulation models provide an efficient way to predict source-demand interactions and the impacts of rule modifications over time and space, in order to set the most appropriate drought mitigation measures. Frequently, generic simulation models are the core of complex decision support systems (DSS). Although a clear and unambiguous definition of DSS is still lacking, two essential characteristics are generally recognised (Loucks, 1995; Reitsma, 1996):

- a DSS is an interactive tool including computer based information and modelling systems;
- a DSS has the purpose of aiding decision makers contributing to understand the problem, to explore alternative courses of actions, to predict their impacts, to facilitate sensitivity analysis.

In recent years, many examples can be found in the literature relating to the use of DSS in water resources, as can be seen in the studies by Labadie et al. (1989) or Loucks and da Costa (1991), among others. The DSS can assist decision-makers to answer specific questions by facilitating the use of models and databases in an interactive way (Andreu et al., 1996). The DSS can support at different levels of details ranging from simple screening models for guiding data collection activities, to more complex tools requiring high levels of expertise. These computer-based prediction models can be combined in a mixed optimization-simulation approach to anticipate the occurrence of water scarcity considering different hydrological scenarios. Despite the potential of using scenario optimization in the search for efficient alternatives, full integration between simulation and optimization has not yet been achieved yet and real world applications are frequently applications of generic simulation models (Sechi and Sulis, 2010).

Generally speaking, there are five steps in simulation modelling used to create a DSS (Loucks and van Beek, 2005):

1. to identify the information to provide;
2. to model the system's behaviour;
3. to put 1 and 2 together and identify a means of entering inputs and obtaining outputs;
4. to calibrate and validate the model;
5. to use the model to produce information.

All models produce simplified representations of real-world systems. Which features are incorporated into the model depend in part on what the modellers have thought is important. Models are all based on some assumptions, and some of these may lead to significant approximations of reality (Sechi and Sulis, 2010).

4.4.2 Evaluated software tools

A large variety of generic simulation models within interactive graphics based interfaces has been developed by public and private organizations. They all are designed to study water related planning and management issues in water systems and to satisfy the needs of those at different levels of planning and decision-making process (Assaf et al., 2008). Several software tools for water resources management at regional-basin scale that are available in the market are evaluated to be used in this study. Each model presented has its own special characteristics; nevertheless a main feature makes the difference between them: AQUATOOL, MODSIM and WEAP are models where optimization methods are developed on the single time period and results are used as an efficient mechanism for performing simulations, whereas the other models are simulation-only models based on a more conventional if-then approach. Main characteristics of all the evaluated software tools are summarized in Tab. 4.1.

Table 4.1 Evaluated software tools for water resources management at regional-basin scale and their main characteristics.

Software	**Water Evaluation And Planning system (WEAP)**
Developed by	Stockholm Environment Institute's U.S.
Website	http://www.weap21.org/ (December, 2010)
Cost (2009)	700€ for accredited academic institution, 2˙000€ for other users
Brief description	WEAP is a reservoirs, rivers and user system water balance accounting model that allocates water from surface and groundwater sources to different types of demands
References	WEAP has been used in studies throughout the world conducted by United Nations agencies, the U.S. Agency for International Development, several other governmental or local agencies and ONG organizations
Software	**MODSIM-DSS**
Developed by	Colorado State University
Website	http://modsim.engr.colostate.edu/index.html (January, 2010)
Cost (2009)	Freeware Software
Brief description	MODSIM-DSS is a generalized river basin DSS and network flow model designed specifically to meet the growing demands and pressures on river basin
References	It is applied in several project located in the USA, Brazil and Europe
Software	**Aquatool**
Developed by	Universidad Politecnica de Valencia, Instituto de Ingenerìa del Agua y Medio Ambiente
Website	http://www.upv.es/aquatool/index_E.htm (December, 2010)
Cost (2009)	From 7˙000€ up to 20˙000€ depending on the purchased modules
Brief description	Aquatool is a DSS for the water resources management. The system consists of a series of modules that are integrated into a single system
References	It is applied to several real cases in Spanish (Júcar, Segura, Tajo...) and worldwide (Argentina, Brazil, Italy, etc.) basins.

continued

Software	OASIS
Developed by	HydroLogics, Inc.USA
Website	http://www.hydrologics.net/oasis.html (December, 2010)
Cost (2009)	Free for research and educational purpose except the module XA (1˙500 $)
Brief description	OASIS software is a tool that enables parties with diverse and often conflicting goals (cities, power facilities, environmentalists, and agriculturalists) to work together to develop operating policies
References	It is applied to several real cases in different states of USA

Software	Water Rights Analysis Package (WRAP)
Developed by	U.S. Geological Survey (USGS) and Texas Water Resources Institute (TWRI)
Website	https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm (October, 2009)
Cost (2009)	Freeware Software
Brief description	The Water Rights Analysis Package (WRAP) simulates management of the water resources of a river basin, or multiple-basin region, under a priority-based water allocation system through different programmes that compose the software tool.
References	The model is applied to the basins of the Texas State and to several basins worldwide, especially in Northern and Southern America

Software	Mike Basin
Developed by	DHI Danish Hydraulic Institute
Website	http://www.dhigroup.com/Software/WaterResources/MIKEBASIN.aspx (December, 2010)
Cost (2009)	8˙500€ + VAT. For educational purposes discount of 50%
Brief description	Mike Basin couples ArcGIS with a hydrologic modelling to provide basin-scale solutions to address water allocation, conjunctive use, reservoir operation and water quality issues. It is not conceived as DSS.
References	It is applied in similar studies for Piemonte Water Resources Action Plan, Italy (2002-2004).

Software	WaterWare: Water Resources Management Information System
Developed by	Environmental Software and Services GmbH Austria
Website	http://www.ess.co.at/WATERWARE/ (October, 2009)
Cost (2009)	Up to 55˙000€
Brief description	WaterWare includes a number of simulation and optimization models and related tools to simulate a broad range of river basin processes
References	It is being developed on the basis of results of the EUREKA project EU487; the initial case study was the Thames basin in England. It is applied to the Lerma-Chapala basin in Mexico, the West Bank and Gaza in Palestine, the Kelantan River in Malaysia and to a series of case studies around the Mediterranean.

Software	WSM DSS
Developed by	National Technical University of Athens (Prof. D. Assimacopoulos) - Ruhr University (Prof. A. Schumann) - ProGEA S.r.l. (Prof. E. Todini)
Website	http://www.progea.net/Pages/WsmDesc.htm (October, 2009)
Cost (2009)	Not available
Brief description	The Water Strategy Man DSS has been developed to satisfy the general needs of Decision Makers and Water Planners in the preparation of management plans
References	WSM DSS is firstly applied for the water management strategies for the Belice Basin (Italy), for the Limassol Region (Cyprus), and then for several basins in Europe

continued

Software	**SOMOS**
Developed by	Utah State University Research Foundation
Website	http://www.usurf.org/units/wdl/somos (October, 2009)
Cost (2009)	10˙000 € circa
Brief description	SOMOS (Simulation-Optimization Modeling System) is a family of simulation and optimization modules aimed at the finest management of water resources
References	SOMOS is applied to several real cases in USA in Oregon, Utah, California, Massachusetts, and Nebraska.

There are several software tools that can be used for water resources management at regional-basin scale, but that are able to solve only some parts of the problem. For example Infoworks RS Integrated Network modelling solution, developed by Wallingford Software Ltd, is an integrated network modelling solution for river systems.
There are some software tools that are now in developing. One of the more interesting is WaterBase (www.waterbase.org). The WaterBase project is an ongoing project of the United Nations University. Its aim is to advance the practice of Integrated Water Resources Management (IWRM) in developing countries. The hydrologic model is developed, but the management part is not still ready.
Several software tools have been evaluated and in the end it was decided to use WEAP mainly for three reasons. First of all because it can simulate a broad range of natural and engineered components of a basin or sub-basin system. Secondly because it is user friendly and it permits to simulate and to compare different possible scenarios, and finally because it has been used in several applications and there is a general agreement about its performances among the scientific and non-scientific communities worldwide. In the next paragraph an extensive description of the chosen software is given.

4.4.3 The WEAP software

The WEAP (Water Evaluation and Planning System) software, developed by the Stockholm Environment Institute's U.S. (SEI, 2005), is implemented for the analysis. It is a reservoirs, rivers and user system water balance accounting model that allocates water from surface and groundwater sources to different types of demands. The modelling system is designed as a tool for maintaining water balance databases, generating water management scenarios, and performing policy analysis. It integrates some physical hydrological processes with the management of demands and infrastructure to allow for multiple scenario analysis, including alternative climate scenarios and changing anthropogenic stressors. Scenarios are story-lines of how a system might evolve or is evolved over time with different hypothesis of river flows. WEAP places demand-side issues such as water use patterns, equipment efficiencies, re-use strategies, costs, and water allocation schemes on an equal footing with supply-side topics such as streamflow, groundwater resources, reservoirs, and water transfers.

WEAP operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems. Moreover, WEAP can simulate a broad range of natural and engineered components of these systems, including rainfall runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analysis; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. Additionally a financial analysis module allows users to investigate cost-benefit comparisons for projects.

The physical hydrology model updates the hydrologic state of the system at each time step, and thus provides mass balance constants used in the allocation phase within the same time step. A groundwater module in WEAP allows for water transfers between stream and aquifer. The main point of the water management analysis in WEAP is the analysis of water demand configuration. These demand scenarios are applied deterministically to a linear programming allocation algorithm where to each demand and source is assigned a user defined priority. The linear programme solves the water allocation problem trying to maximize satisfaction of demand, subject to supply preferences and demand priorities, and using reservoir operating policies to minimize the distance to ideal conditions. The water allocation problem is solved at each time step using an iterative, computationally expensive approach. Traditional target storage levels, multiple zones, and reduced releases by a buffer coefficient are implemented in WEAP. Supply balancing within demand centres with the same priority is assured by that approach. WEAP requires significant data for a detailed analysis.

A WEAP characteristic that is very interesting for the development of this study is the demand management capability. WEAP has the capacity of representing the effects of demand management on water systems. Water requirements may be derived from a detailed set of final uses, or water services in different economic sectors. For example, the agricultural sector could be broken down by crop types, irrigation districts and irrigation techniques. An urban sector could be organized by county, city, and water district. Industrial demand can be broken down by industrial subsector and further into process water and cooling water. This approach places development objectives, providing end-use goods and services, at the foundation of water analysis, and allows an evaluation of effects of improved technologies on these uses, as well as effects of changing prices on quantities of water demanded. In addition, priorities for allocating water for particular demands or from particular sources may be specified by the user.

WEAP has been used in studies throughout the world conducted by United Nations agencies, the U.S. Agency for International Development, and several other governmental or local agencies and ONG organizations.

WEAP is structured as a set of five different views of the modelled study area. These views are listed as graphical icons on the "View Bar", located on the left of the screen. For the Results and Overviews view, WEAP will calculate scenarios before the view is displayed, if any changes have been made to the system or the scenarios.

The Schematic view is the starting point for all activities in WEAP. A central feature of WEAP is its drag and drop graphical interface used to describe and visualize the physical features of the water supply and demand system. This spatial layout is called the schematic. It is possible to create, edit and view it in the Schematic view. GIS layers can be added for clarity and impact.
In the Data view data structures, models, and assumptions in WEAP are created. In this view, the screen is divided into four panes. On the top-left, a hierarchical tree is used to create and organize data structures under six major categories: key assumptions, demand sites, hydrology, supply and resources, environment, and other assumptions. The tree is also used to select the data to be edited, which is shown on the right of the screen. For example, clicking on the demand sites tree branch on the left of the screen, it will display the data for all demand sites on the right of the screen. On the bottom left there is a dataset schematic. Clicking on an element in the schematic will result in a jump to its place on the tree. On the top-right of the screen, a data entry table is used to edit data and create modelling relationships.
The Results view displays a wide variety of charts and tables covering each aspect of the system: demand, supply, costs, and environmental loadings. Customizable reports can be viewed for one or more scenarios.
The Overviews view is used to group together favourite charts (created earlier in the Results view) that can then be displayed on the screen simultaneously. With overviews, a birds' eye perspective on different important aspects of modelled system, such as demands, coverage, storage levels, environmental impacts and costs is given.
The Notes view is a simple word processing tool within which enter documentation and references for each branch of the tree.

4.5 THE MODELIZATION

4.5.1 Analysed system

The methodology is applied to the urban area of Firenze in central Tuscany, in central Italy (Fig. 4.2). The catchment of the investigated area has a surface of 1.230 km^2. It covers the Sieve River basin, a right affluent of Arno River, and the Arno River basin between the confluence with Sieve River and the city of Firenze.
It includes Bilancino reservoir, located in the upper part of Sieve catchment. The dam is an earth fill dam with a silt core, a length of 710.0 m, and a maximum height of 41.78 m. The reservoir has a total capacity of 84.50 Mm^3 and a conservation storage capacity of 62.50 Mm^3. The reservoir catchment has an area of 149 km^2, generating mean annual inflows of 78.37 Mm^3, therefore annual inflows frequently exceed the storage capacity of the reservoir.. The flow seasonality is strong with higher values in spring and autumn, although there is not a high annual variability. The flow spatial variability is not pronounced, since the climatic and morphologic characteristics are quite homogeneous in the whole basin. Most of its releases are used to satisfy ecological flow requirements and to supply several municipalities in the area of Florence.
The considered demand centres are Firenze and Bagno a Ripoli, which have, accordingly to the census ISTAT 2001, a total of 395˙000 inhabitants.

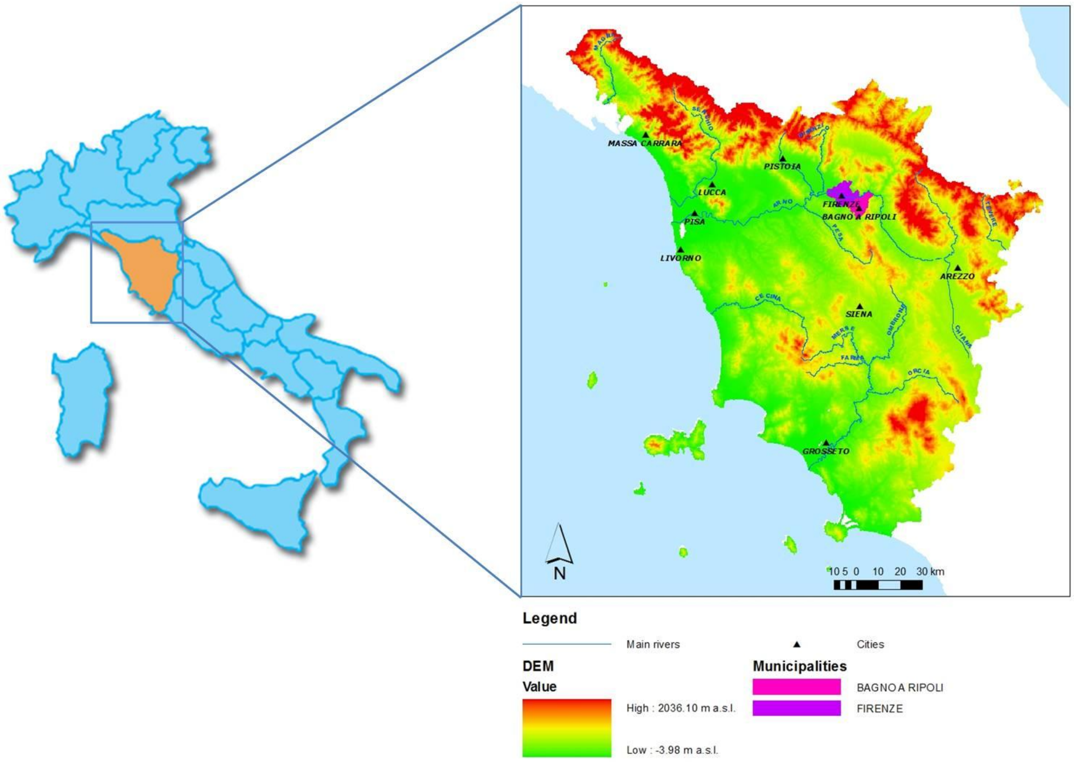


Figure 4.2 Localization of the case study area.

The area was affected by a severe drought in 1985: in that year there has been no precipitation in central Tuscany between April and October; to overcome the problems to the water supply systems the Protezione Civile (Civil Defence Agency) built a pipe to connect the urban area of Florence with some small lakes (Renai di Signa lakes) that are 6 km far apart (Mannucci, 1985). Another drought affected the area on the period 1990 – 1993. Its effects were particularly heavy in the water supply system in the summer 1993.

4.5.2 Model implementation

The scheme of the system is simplified (Fig. 4.3), considering one reservoir, Bilancino, two urban demand sites, Firenze and Bagno a Ripoli, three “river systems”, Arno, Sieve and Sieve Bilancino and two minimum stream flow requirements: the first one on Sieve Bilancino, downstream Bilancino Reservoir, and the second one on Arno, downstream Anconella outlet.

WEAP allocates water to meet instream and consumptive requirements, subject to demand priorities, supply preferences or other constraints. In the model the higher priority is given to the flow requirements, then to the municipality demand centres. The lower priority is given to the reservoir filling: if there is water availability the reservoir level increases, otherwise the water in the reservoir is used to satisfy the other demands.

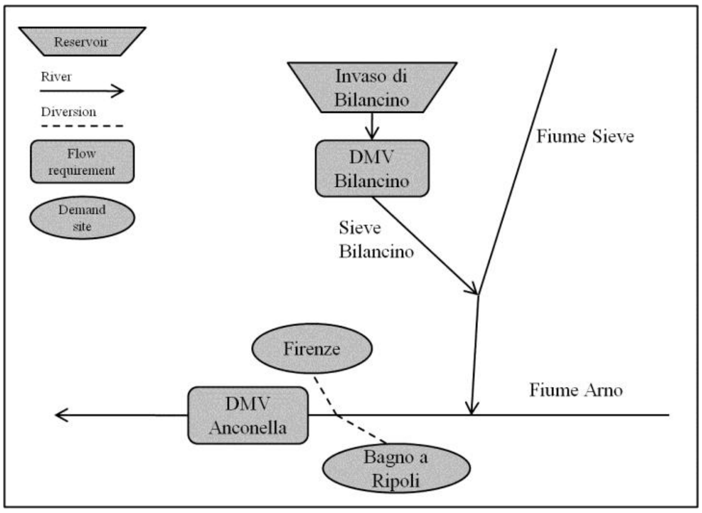


Figure 4.3 Evaluated model of water supply system of Firenze area.

Inflows into Bilancino reservoir and Arno and Sieve rivers discharges are evaluated with the historical data of gauge stations by Servizio Idrologico Regionale Toscano (Regional Hydrologic Service of Tuscany). For Arno River data from Nave di Rosano gauge station (discharge measures 1931-2005) are used and for Sieve River data from Fornacina gauge station (discharge measures 1960-2005) are used. Both the stations have at least 350 days of registration per year. The discharge in Sieve Bilancino is evaluated upper Bilancino as the inflow in the reservoir and downstream Bilancino as the outflow from the reservoir. The inflows in the reservoir are evaluated with data from the gauge stations Ponte di Bilancino till the year 1983; to obtain data from 1984 an annual correlation between the station of Ponte di Bilancino and the station Fornacina is established. A second degree correlation is used. The different degrees of correlation are represented in Fig. 4.4. The second degree was chosen because it fits well the values and has a deeper physical meaning than the third degree correlation.

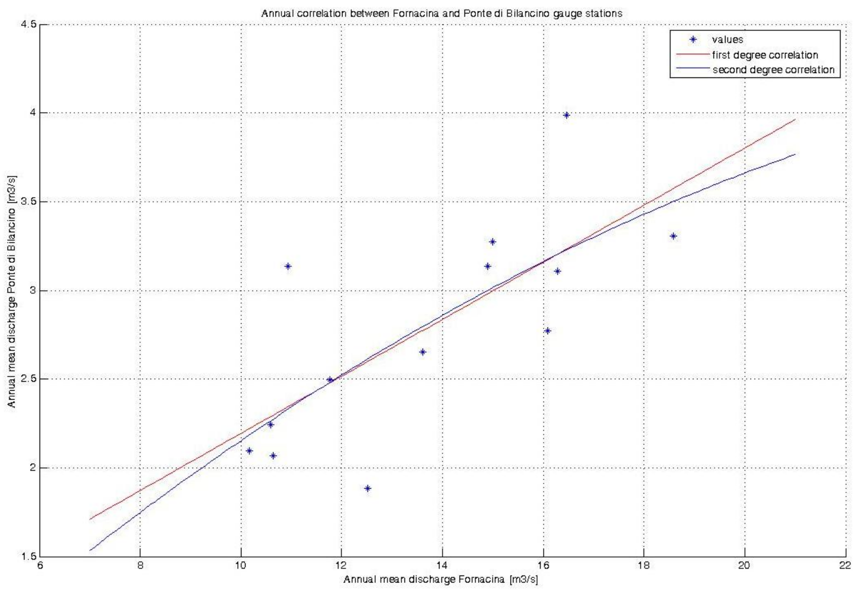


Figure 4.4 Annual correlation between Fornacina and Ponte Bilancino gauge stations.

The total demand (45.591 Mm^3/yr for Firenze and 1.986 Mm^3/yr for Bagno a Ripoli) and the monthly fluctuation (Tab. 4.2 – Fig. 4.5) of urban sites in 2005, evaluated with data from Publiacqua, the local water supply company, are considered as constant in all the simulated years. The internal losses are estimated the 36% of the total demand for Firenze network and the 28% of the total demand for Bagno a Ripoli network.

Table 4.2 Monthly fluctuation (10^3 m^3) for the demand centres of Firenze and Bagno a Ripoli.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Firenze	5266.0	4642.5	4870.9	4722.7	4988.2	5062.3	5266.0	5099.3	5673.5	5858.7	5124.0	5161.1
B. Ripoli	295.4	253.2	253.2	253.2	253.2	139.4	146.3	161.2	231.3	303.7	305.5	277.9

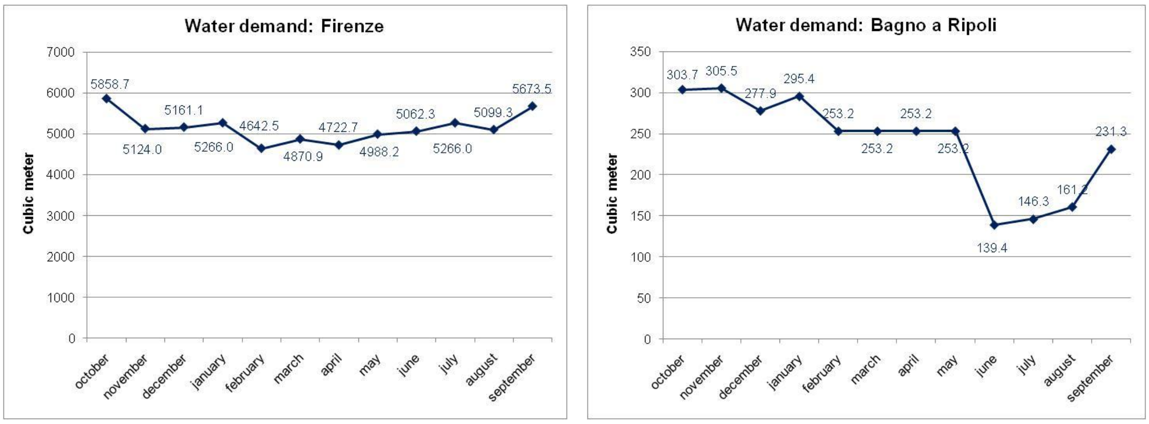


Figure 4.5 Firenze and Bagno a Ripoli municipalities monthly total demand.

A major problem in the management of rivers has been how to balance the tradeoffs between instream (e.g. aquatic life, and recreation) and out of stream (e.g. reservoir regulation) uses. Management problems normally exacerbate during low-flow periods and with ongoing water resources development resulting in gradual reduction of flow available for instream uses.

Heicher (1993) outlined a number of possible environmental effects caused by instream flow reduction. Such reduction may lead to increased sedimentation that changes the morphology of the stream channel and flood plain. Changes in stream morphology may potentially affect the distribution and abundance of stream biota. Streamflow reduction can also aggravate the effects of water pollution. Winds, bank storage, spring seepage, tributary streams, and the warming effect of the sun usually have a greater effect on stream water temperatures during low-flow periods. With the overall reduction in flow, the influence of these factors increases. Lowering the water table or reducing overbank flooding may result in changes in the density, productivity, and species composition of wetland and riparian vegetation. Streamflow reduction may cause changes in the relative abundance of algae, allochthonous material and organics, which may influence the abundance and distribution of benthic macroinvertebrates. Changes in aquatic habitat caused by extended low-flow periods may result in long-term changes in species distribution and abundance. Increased siltation and adverse

water quality effects associated with unnaturally persistent low flows can alter the distribution and abundance of fishes.
Traditionally, the problem of balancing instream and out of stream uses has been addressed by optimizing the economic benefits of flow diversions and reservoir releases with instream uses as a flow constraint (Smakhtin, 2001). Two flow requirements are present in the modeled area. A first instream condition is downstream Bilancino Reservoir and has the main goal to preserve the physical characteristics of water bodies, chemical and physical properties of water and to maintain the different species living in Sieve River ecosystem. It has a value of 0.6 m^3/s and it is calculated by Arno Basin Authority.
The flow requirement upstream Florence urban area has a value of 8.0 m^3/s and it is established for environmental considerations, especially to preserve chemical and physical properties of water on urban part of Arno river summer discharges. The flow requirement on Arno has the same water allocation priority as water supply to municipalities, so that its requirement will not heavily affect the coverage of Firenze water supply (AdB Arno, 2001).
The storage capacity of Bilancino is evaluated as the conservation storage capacity: 62.50 Mm^3. Bilancino reservoir is supposed to be fully operational since 1970, although it was finished in 1995, in order to reproduce current drought risk in the system. The evaporation is evaluated with Revfeim and Jordan (1976) polynomial formula.

$$Ev(T) = aT^2 + bT + c \tag{4.1}$$

where: Ev is the daily evaporation [mm]; T is the mean daily temperature for the station Borgo San Lorenzo [°C]; a, b, and c are empirical coefficients evaluated accordingly with the data of the evaporimeter placed near the dam in the years 1998-1999. It is obtained: a=0.0037 b=0.0274 c=0.2552.
Loss to groundwater can be divided into: losses trough the dam and loss trough the bottom of the reservoir. Both are negligible: the first ones because are less than 150 l/min (less than 6000m^3/month), the second ones because the soil is impervious and clayey.
The relationship between failures of water supply systems and reservoirs volumes, represented by volume in reservoir – deficit/risk curves, is evaluated performing short time simulations.
At a first attempt each simulation is performed considering a time lag of two years, then considering a time lag of one year. We performed the simulation even with a time horizon of three years considering the empty reservoir at the beginning of the simulation (worst condition). We decided not to perform these simulations because the effects of the drought, even with the worst condition (empty reservoir at the beginning of simulations), do not last for three years.
The two-years time horizon may be chosen because the effect of reservoir initial filling influenced the drought conditions of the system for the following two years. The simulations for the season reference months are performed with one-year and two-years time lag but in the end we have decided to analyse all the possible situations for the one year time horizon for two main reasons. Firstly because we verify that only for

four couple of years there is an influence on the second year (12%), and secondly because in reality it is difficult to manage a system imposing rules to save water in order to prevent a supply crisis in the following years.
A Monte Carlo simulation based on historical inflow record is carried out. The simulations were performed considering 25 different amounts of water stored in the reservoir at the beginning of the simulation (boundary conditions) combined with the inflows of various periods. Particularly we used an ensemble of 420 inflows, consisting each in 12 consecutive monthly recorded inflows. The set is obtained by taking each time a different first month within the considered time series of 35 years, from January 1970 to December 2005. The process began with the simulations starting in October, the first month in the hydrological year in Tuscany, and in July, the first month of hydrological summer. With the results for these months it was decided to distribute the 25 degree of filling in unequal intervals: 20 intervals between 0% and 50% (every 2.5%) and 4 intervals between 50% and 90%. It was decided not to simulate the situation with a filling greater than 90%, because of the low probability of having an unmet demand with a full reservoir. Then simulations were performed, only for the one-year time step, starting in all the 12 months.

4.5.3 Simulations results processing

Once the simulations were performed, the results were processed to obtain, for every month, the required storage volume in month m, v^{m}_{dr}, for a given deficit level d_i and risk level r_j. The following procedure was applied:

- For every initial storage volume analysed, the cumulative probability distribution of deficits is estimated from the sample of results of the simulations over the ensemble of inflows (Fig. 4.6).

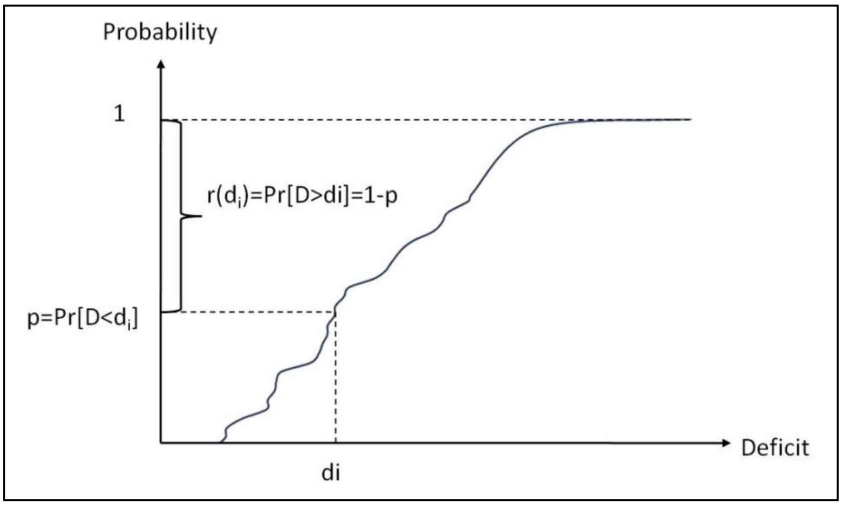


Figure 4.6 Simulations for a given storage volume in month m, over the ensemble of inflows.

- For the deficit value selected, d_i, the risk $r(d_i)$, defined as the probability of having a deficit equal to or larger than the selected value is obtained.

- The curve [v^m, $r(d_i)$], relating initial storage values to risk for the deficit value selected, is built (Fig. 4.7).
- From the curve, the storage volume, v^m_{dr}, corresponding to deficit level d_i and risk level r_j, is selected.

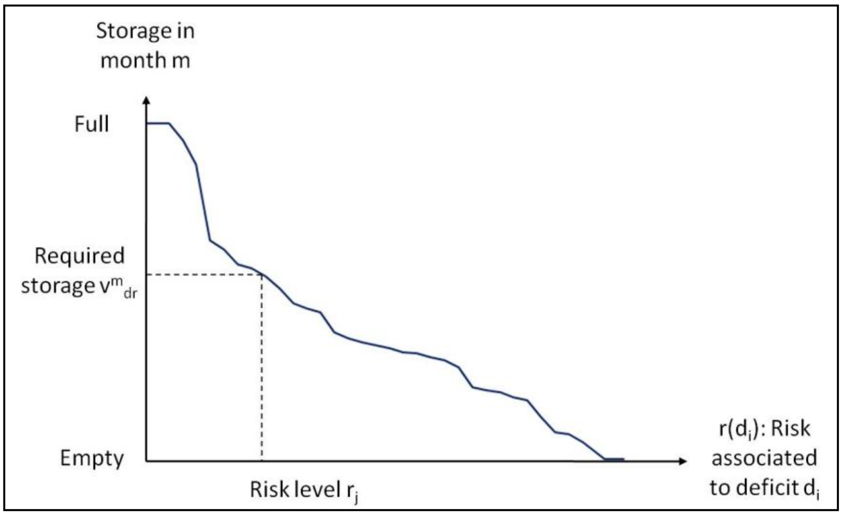


Figure 4.7 Storage volumes in month *m* as a function of risk values for a deficit level d_i.

This procedure was applied to obtain the charts presented in the following figures. Once the simulations are performed a level of deficit is found for every year or couples of years, for every starting month and level in the reservoirs. With this information it is possible to define the risk and the amount of failure for each situation. Some graphs are presented to illustrate the results. There are four variables: level of deficit, level of risk, volume stored in the reservoir and simulation start (first considered month). In each graph a first variable is set and the variability of a second one, function of the other two, is represented. The graph for the two-years time horizon (in black and white) and for the one year time horizon (in colours) are presented.

In the first group of graphs (Fig. 4.8) the stored volume in four reference months, function of the deficit, function of risk, is represented. The chosen months are October, January, April and July, the first ones of each hydrologic season. The deficit is represented with four curves, function of four level of risk: 5%, 15%, 30% and 50%. These levels are chosen because are quite representative. There is no deficit till the critical volume is reached, and then there is a nearly linear correlation between stored volume and deficit. The results for one year time horizon simulations can be compared with the ones fort the two-years time horizon. In Fig. 4.9 the graphs for the month of October, January, April and July with the same variables used in the one year time horizon are presented. The results of the different time horizons are similar, with a linear correlation between the variables. Only the deficit scale is different. In two-years time horizon simulations the values are lower, since the effect of drought in the second year is quite low. For the 5% risk in the month of January a 0% of deficit is never reached, due to the droughts of 1970-1972 that is not overcome with these reservoirs volumes.

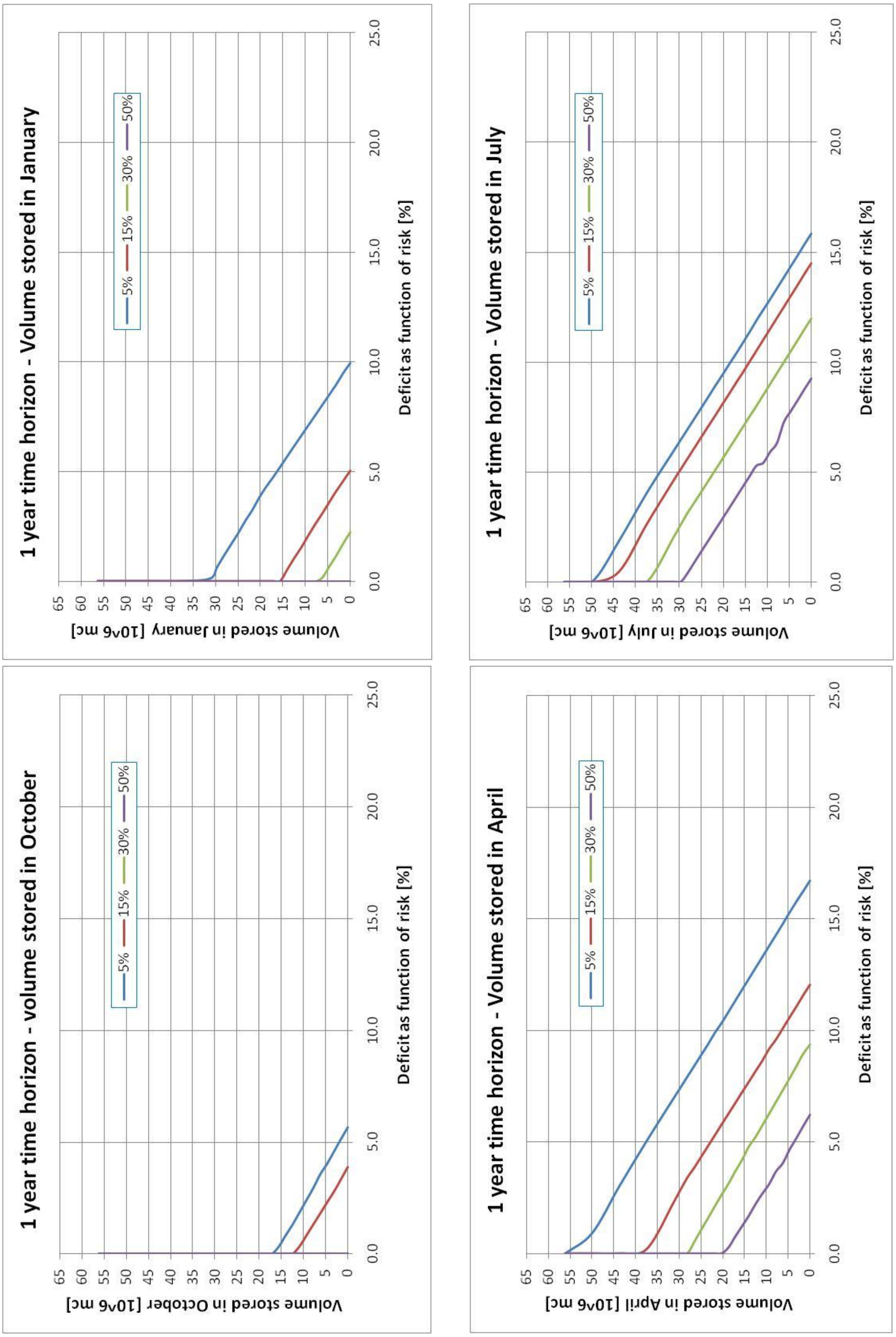


Figure 4.8 Results of analysis for one year time horizon: **stored volume** in four reference months (Oct-Jan-Apr-Jul) function of **deficit** for four selected risks (5%, 15%, 30%, and 50%).

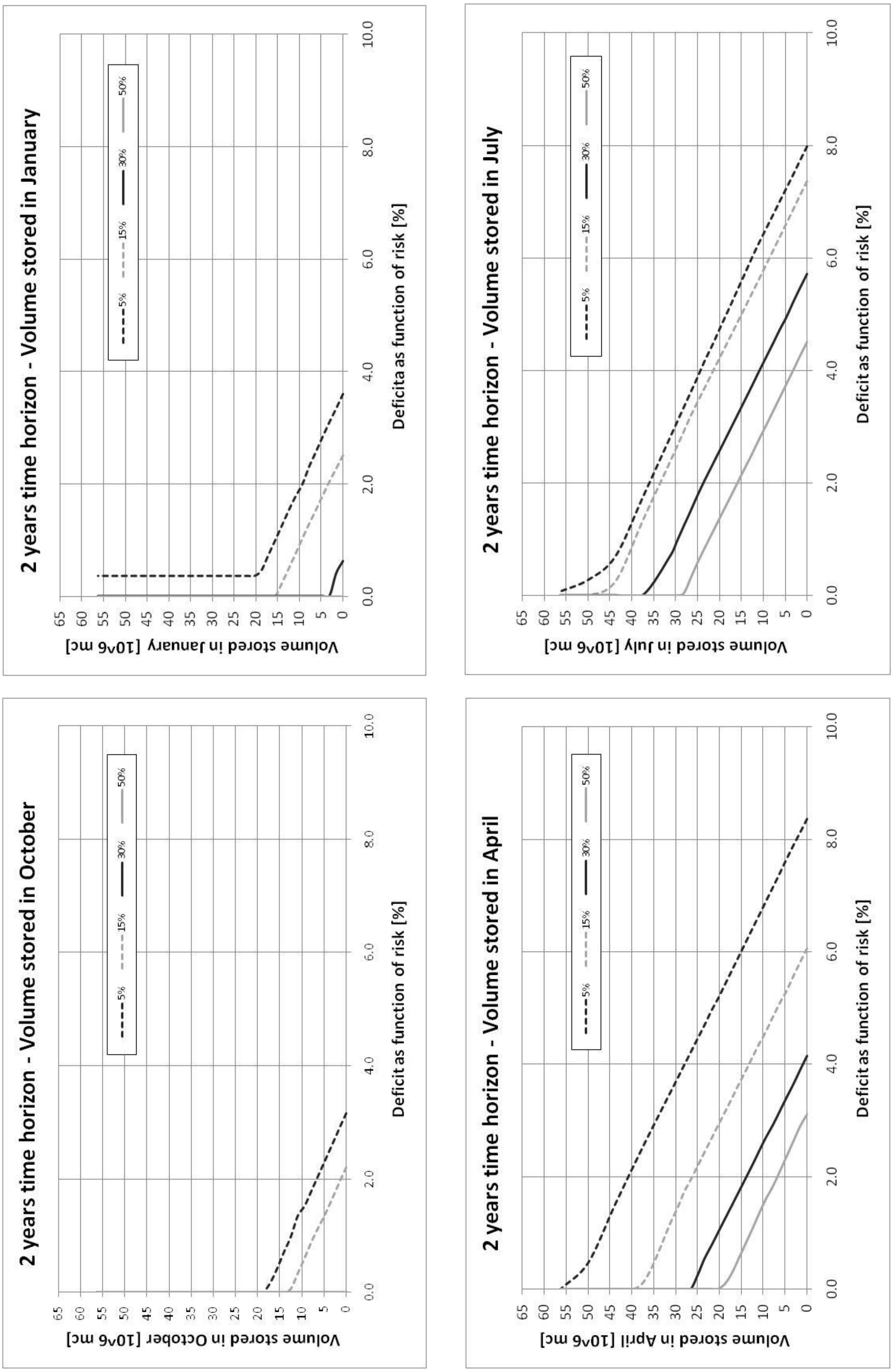


Figure 4.9 Results of analysis for two years time horizon: **stored volume** in four reference months (Oct-Jan-Apr-Jul) function of **deficit** for four selected risks (5%, 15%, 30%, and 50%).

In the second group of graphs (Fig. 4.10) the risk of failure for one-year time horizon and four stored volumes, function of the deficit for the first months of each hydrological season, is represented. The chosen stored volumes of 0.00 m^3 (0%), 12.50 m^3 (20%), 25.00 m^3 (40%), 37.50 m^3 (60%) are a partition in equal intervals between the empty reservoir and the maximum volume with significant levels of deficit. A higher stored volume for October than for January, for April than for January and in most of the cases for July than for April is needed. There is a nearly linear correlation between risk of failure and deficit, even if the results are more biased than in the case volume-deficit. The comparison with two-years time step (Fig. 4.11) shows the same performances and a difference in absolute values, for the same reasons explained above. Even for the two-years time horizon the risk of failure in July is always higher than the one in April for big amount of water stored in the reservoir.

In the third group of graph (Fig. 4.12) the required volume month by month for one year time horizon is represented. Only the results for the one year time horizon are shown since that for the two-years time horizon were not performed all the necessary simulations. Four deficit levels were considered: 0%, 2%, 5% and 10% of the demand. These levels are relevant for decision making, because they correspond to significant degrees of socioeconomic impacts. For each deficit value, the required storage volume at the beginning of every month was computed for different risk values. A total of six risk values were considered: 0%, 5%, 10%, 20%, 30% and 50%.

Required volumes are maximum in summer and minimum in winter, in accordance with hydrologic regime. For the 10% deficit the required volume is very low. This means that the system is not totally depending from the reservoir.

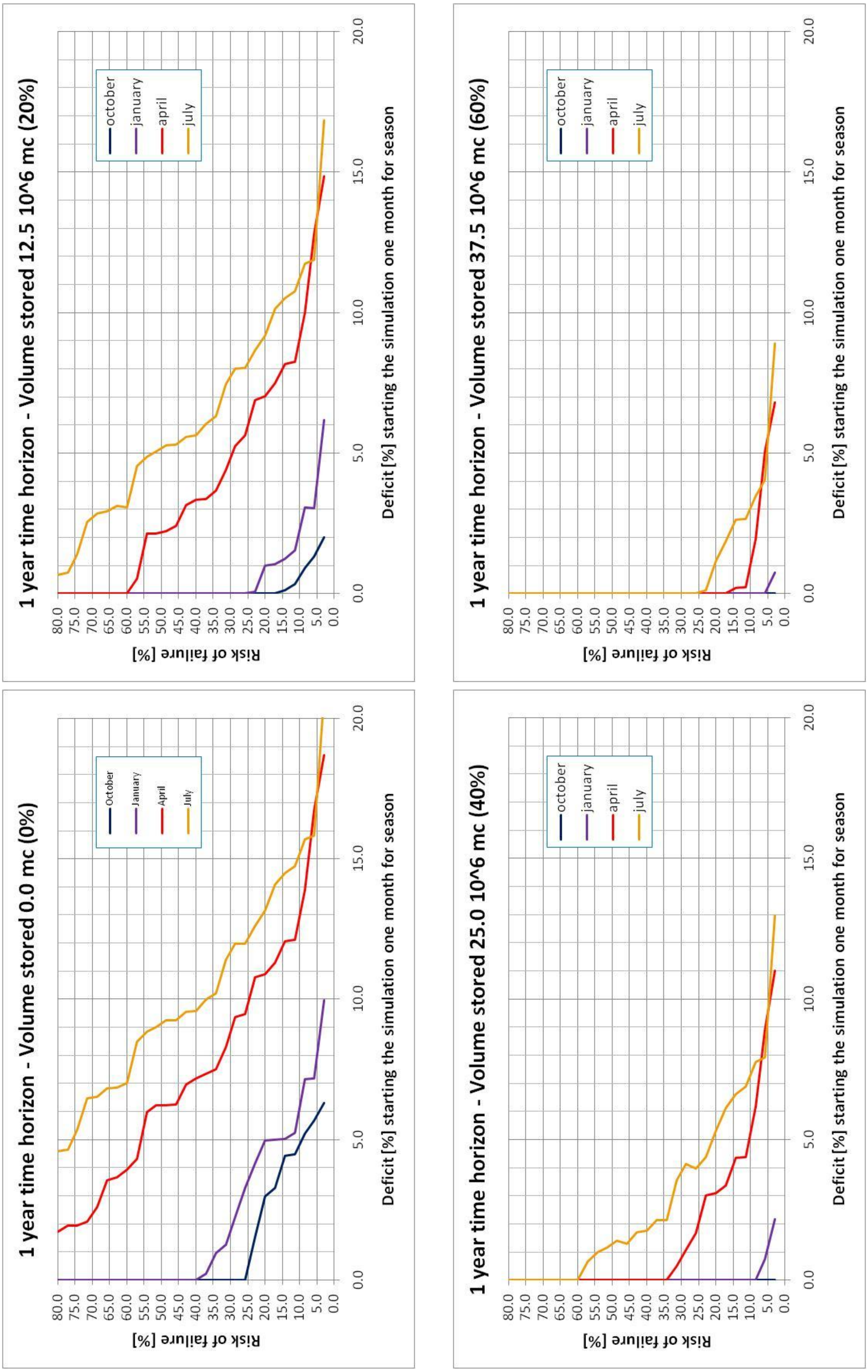


Figure 4.10 Results of analysis for one year time horizon: risk of failure for four stored volume function of deficit for four reference months (Oct-Jan-Apr-Jul).

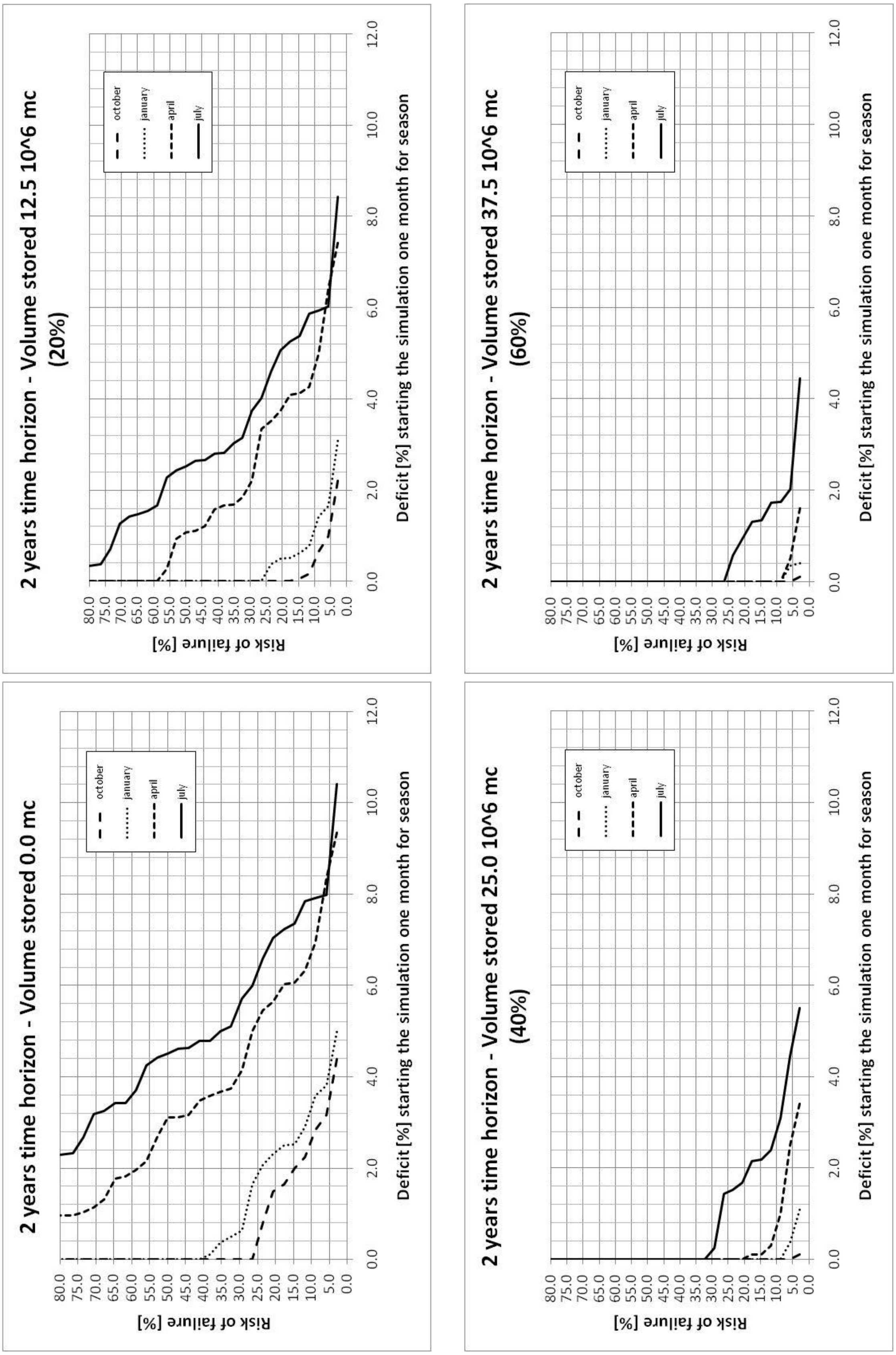


Figure 4.11 Results of analysis for two-years time horizon: risk of failure for four stored volume function of deficit for four reference months (Oct-Jan-Apr-Jul).

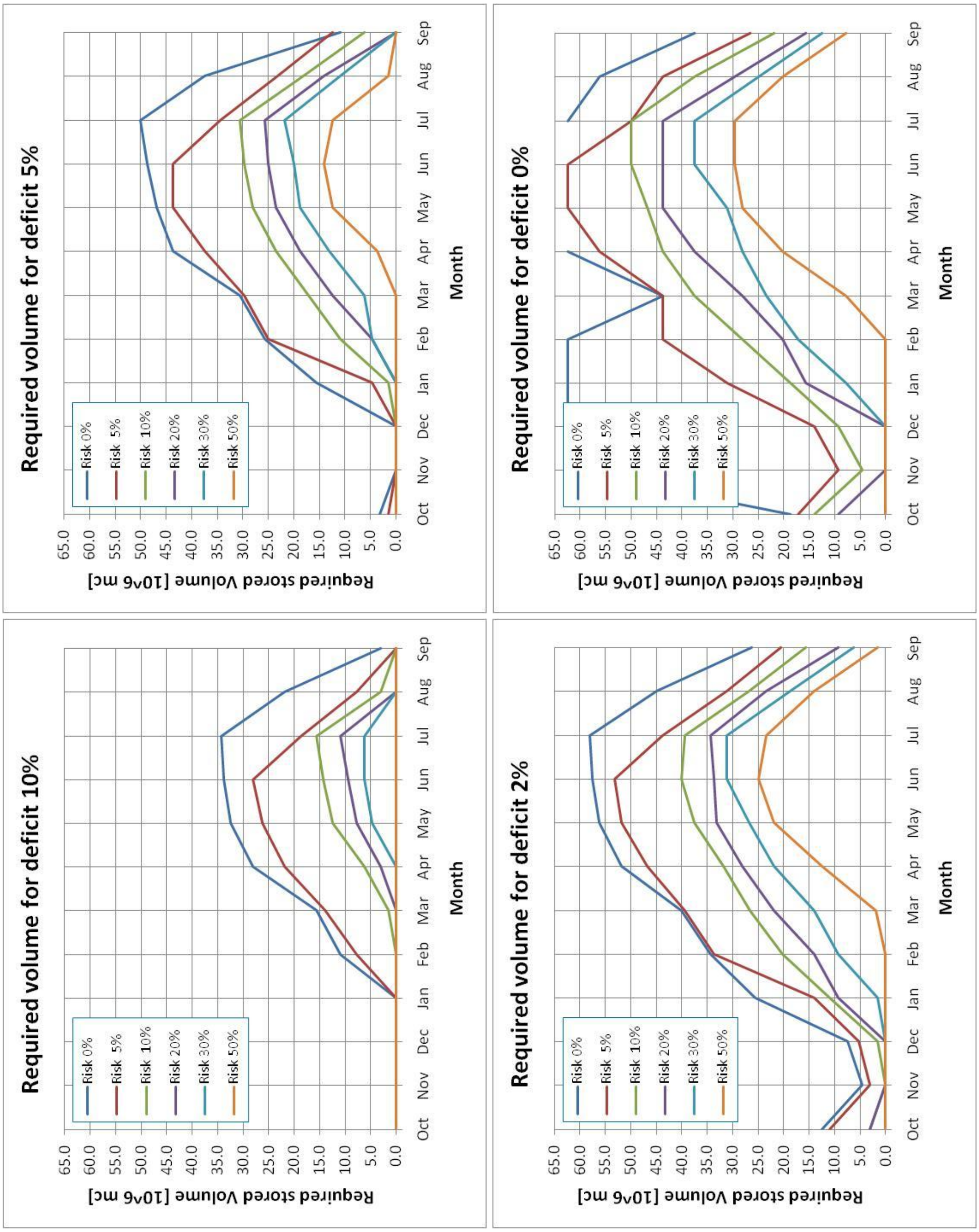


Figure 4.12 Required reservoir volumes in different months for four considered deficits and six degree of risk of failure (0%, 5%, 10%, 20%, 30%, and 50%).

CHAPTER 5 – DROUGTH RISK MITIGATION: RESERVOIRS MANAGEMENT OPTIMIZATION

5.1 DROUGHT MITIGATION

A river basin planning, in its narrower and more technocratic form of water resource management has been practiced in many parts of Asia and Africa for at least nine thousand years. The oldest recorded practice of irrigated agriculture has been traced in Jericho in 7000 b. C. (Hirsch, 1959). There are also recorded histories of scientific water management, including quite sophisticated engineering works for water regulation in China, Egypt and Iraq which go back to several thousand years. Ancient text and actual waterworks systems in these countries indicate the remarkably sound knowledge about water cycle and engineering and social aspects of irrigation (Petersen, 1984).

Mitigation can be defined as any structural or physical measures (e.g. appropriate crops, sand dams, and engineering projects) or non-structural measures (e.g. policies, awareness, knowledge development, public commitment, and operating practices) undertaken to limit the adverse impacts of natural hazards, environmental degradation, and technological hazards. The primary goal of an effective drought strategy is to lessen the risk associated with severe drought events and therefore reduce impacts (Wilhite, 2008). It is clear that neither centrally directed nor purely private sector approaches provide the organization model needed to solve problems like these. What is needed is what White (1969) called "multiple means". They require comprehensive management frameworks with roles for water managers, elected officials, community leaders, educators, and common citizens in a long term coordinated effort to identify and implement the needed actions (Grigg, 1996). The policy should be consistent and equitable for all regions, population groups and economic sectors and consistent with the goal of sustainable development.

During the years several economic instruments to cope with drought were developed. Credit markets, agricultural insurances, insurances based on drought indices, compensatory schemes were developed to cope with agricultural drought (Liso, 2001). Water markets (Luo et al, 2007, Calatrava and Garrido, 2005), risk sharing instruments (Hurt, 2005), water banks and water transfers (Israel and Lund, 1995), pricing mechanisms and awareness campaigns (Syme et al, 2000) were developed to cope with hydrological droughts and water shortages. Information campaigns and educational activities are planned to encourage a rational use of water and a change of habits. Despite being part of a wider plan to use water efficiently, they have not a secondary importance because dialogue and public participation are essential for an efficient water management. Participation reduces conflicts between citizens and decision makers, sharing the made choices (APAT, 2006). Evidence from several campaigns shows that awareness building can effectively reduce water demand. Persuasion campaigns for demand management are most effectives in periods of droughts or water shortages. Some campaigns show that it is possible to save up 12% of water demands with a cost in the range of 0.3€/m^3 (Syme et al., 2000).

The selection of risk management options must be evaluated in the context of numerous constraints and issues. Some constraints could include time, financial and personnel resources, geography, feasibility, the level and nature of development and vulnerability, the attitudes and desires of the affected communities and landowners, legalities, public acceptance, and liability. They must also take into account social factors such as gender, age, and social and economic capacities. Women, children, the elderly, and the poor are especially vulnerable to the effects of drought. Special consideration must be given to these populations and those livelihoods least able to cope with drought (UN/ISDR, 2007).

5.2 RESERVOIRS MANAGEMENT UNDER DROUGHT CONDITIONS

One of the most common ways to mitigate drought effects is to build and manage a dam. A dam stores water and permits to reuse it in different time during the year or among years. Once a dam is built, it is very important for system managers to develop methods, rules and criteria to evaluate water scarcity and prioritize proactive and reactive measures for drought management, especially in well-developed regions with extensive hydraulic infrastructure and complex socio-economic interactions.

Sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity (ASCE, 1998). Objective functions used in reservoir system optimization models should incorporate measures such as efficiency (i.e., maximizing current and future discounted welfare), survivability (i.e., assuring future welfare exceeds minimum subsistence levels), and sustainability (i.e., maximizing cumulative improvement over time). In large systems, mathematical simulation and optimisation models may be used to evaluate the effect of management operational rules, water conservation measures, and scheduling available actions (Cai et al., 2002).

Despite several decades of intensive research on the application of optimization models to reservoir systems, authors such as Yeh (1985) and Wurbs (1993) have noted a continuing gap between theoretical developments and real-world implementations. There are several possible reasons for this disparity. Firstly many reservoir system operators are sceptical about models purporting to replace their judgment and prescribe solution strategies and feel more comfortable with use of existing simulation models; secondly computer hardware and software limitations in the past have required simplifications and approximations that operators are unwilling to accept; in addition optimization models are generally more mathematically complex than simulation models, and therefore more difficult to comprehend; then many optimization models are not conducive to incorporating risk and uncertainty; finally some optimization methods, such as dynamic programming, often require customized programme development (Labadie, 2004).

Many of these hindrances to optimization in reservoir system management are being overcome through ascendancy of the concept of decision support systems and dramatic advances in the power and affordability of desktop computing hardware and software. Several private and public organizations actively incorporate optimization models into reservoir system management through the use of decision support systems (Labadie et al., 1989). Incorporation of optimization into decision support systems has reduced resistance to their use by placing emphasis on optimization as a tool controlled by reservoir system managers who bear responsibility for the success or failure of the system to achieve its prescribed goals.

In the case of reservoir systems there is a growing need to develop more sophisticated operation rules in order to consider new interconnections between the components of the water supply system, to better cope with deficits caused by more frequent droughts and increasing demands as well as to satisfy new ecological constraints in rivers (Rossi et al., 2007b).

Reservoir operating rules specify releases as a function of system state for normal and exceptional conditions of water excess (floods) or deficit (droughts). The focus of this work is on operating rules under drought conditions. The magnitude of reservoir releases during drought periods deals with the unknown inflows to be experienced between the time of decision and the end of the drought. Caution, entailing keeping as much water in storage as possible, must be balanced against the need to provide as large proportion of the normal supply requirement as possible, minimizing, for example the degree of rationing (Sargent, 1979).

Analysis of reservoirs management under drought conditions has received increasing attention in the last years, especially the optimization of the rule curves and of the operational procedures (Hsu et al., 2004; Chang et al., 2005; Cañón et al., 2009).

Reservoir operation rules under drought conditions are based on proactive measures, to be adopted before drought impacts occur. They imply demand management, imposing some temporary and moderate demand reductions in order to prevent catastrophic failures in the future. The great variability on the natural water resources and also on the demands is faced defining some threshold values to activate the implementation of measures. Thresholds are expressed in probabilistic terms that measure the hydrologic state of the system. They define four scenarios associated with different levels of drought severity that are, following the subdivision of Iglesias et al. (2007): normal, pre-alert, alert and emergency scenarios. They can simplify the decision-making required during stressful periods and can help to mitigate the impacts of drought by clearly defining the conditions requiring actions.

This part of the research has the objective of defining the operating rules of a water system devoted to urban supply under drought conditions. The rules to manage the system in drought conditions, the threshold levels and the reductions are optimized using a long term simulation in which a 35 year time series is considered. The critical situations are assessed month by month in order to avoid conditions of total water shortage. In particular the optimal releases, obtained by an optimization technique with a given objective function, represent the basis for deriving operation rules to be provided to water supply system operator. The analysis considered a water system including a reservoir regulating part of the surface waters and some urban demand centres.

5.3 DROUGHT CHARACHTERIZATION

The classification of drought risk in different levels responds to the need to design measures in the most effective way to ensure that they are accepted and supported by the stakeholders. Each of these risk levels is associated with a clearly defined objective that determines the type of measures to be implemented. The threshold values are defined considering the probability to satisfy a given fraction of the demand in a certain time horizon, and would be calibrated through discussions with water managers. A demand reduction is related to each threshold level. A drought trigger is the specific value of a drought indicator that activates a management response. For example, a drought trigger could be a reservoir decreasing below 50% of its storage capacity. In a drought contingency plan, trigger levels can be varied to alter the sensitivity of the response and the effectiveness of the plan. Defining drought triggers can be difficult. Trigger levels change over time, that is, an appropriate trigger level for a particular system may change dramatically if that system has an increase in available infrastructure or if water demands change dramatically. Urban water triggers are often quite different from agriculture drought triggers, as the urban infrastructure can often mitigate the impacts of short-term droughts (Palmer et al., 2002).
Drought responses are predefined management actions that are activated by a trigger. Short-term responses can include the initiation of outdoor water use bans, the increase of the price of water, or the use of printed media to inform the public of water supply problems. Drought management plans for many urban areas are often developed with three to five levels of responses, all of which encourage different levels of demand reduction or supply augmentation. The effectiveness of drought responses is dependent upon the community. An outdoor water ban, for instance, may be effective for a residential community but not for a heavy industrial community.
In this work thresholds are expressed in probabilistic terms that measure the hydrologic state of the system. They define four scenarios associated with different levels of drought severity that are, following the subdivision of Iglesias et al. (2007): normal, pre-alert, alert and emergency scenarios.

- **Normal Scenario**: the values of the indicators are above the threshold for pre-alert and it is not necessary the adoption of any particular measure.
- **Pre-alert Scenario**: the values of the indicators are included among the pre-alert and warning thresholds, which correspond to moderate risk of consuming all water stored in the system not being able to meet water demand. The pre-alert scenario is declared when monitoring shows the initial stage of drought development. The management objective in the pre-alert scenario is to prepare for the possibility of a drought. This means to ensure public acceptance of measures to be taken if drought intensity increases by raising awareness of the possibility of societal impacts due to drought. The kinds of measures that are taken in the pre-alert situation are generally of indirect nature, are implemented

voluntarily by stakeholders and are usually low cost. The main goal is to prepare the organism and the stakeholders for future actions. Main necessary actions are intensification of monitoring, usually through the creation or activation of drought committees, and evaluation of future scenarios, with special attention to worst case scenarios. Generally, prevention non-structural measures are taken, aimed at reducing water demand with the purpose of avoiding alert or emergency situations.

- **Alert Scenario**: the values of the indicators range from warning and emergency thresholds. The alert scenario is declared when monitoring shows that drought is occurring and will probably have impacts in the future if measures are not taken immediately. There is a significant probability of having water deficits in the time horizon. The management objective in the alert situation is to overcome the drought avoiding the emergency situation by enacting water conservation policies and mobilizing additional water supplies. These measures should guarantee water supply at least during the time span necessary to activate and implement emergency measures. The kind of measures that are taken in the alarm situation are generally of direct nature, are coercive to stakeholders and are generally of low to medium implementation cost, although they may have significant impacts on stakeholders' economies. Most measures are non-structural, and are directed to specific water use groups. Demand management measures include partial restrictions for water uses or water exchange between uses. This may be a potential source of conflict because user rights and priorities under normal conditions are overruled, since water has to be allocated to higher priority uses.
- **Emergency Scenario**: the indicators are already at values lower than the emergency thresholds. The emergency scenario is declared when drought indicators show that impacts have occurred and supply is not guaranteed if the drought persists. It is a critical situation in which exceptional measures are unavoidable to ensure urban water supply, environmental flows, power plants, and, as far as possible, volumes for irrigation. The management objective is to mitigate impacts and minimize damage. The priority is satisfying the minimum requirements for drinking water and crops. Measures adopted in the emergency scenario are of high economic and social cost, and they should be direct and restrictive. Usually there has to be some special legal coverage for exceptional measures, which are approved as general interest actions under drought emergency conditions. The nature of the exceptional measures could be non-structural, such as water restrictions for all users (including urban demand), subsidies and low interest loans, or structural, like new infrastructure, permission for new groundwater abstraction points and water transfers.

This approach requires the definition of objective criteria to declare each of these scenarios on the base of quantitative values. Three important parameters are relevant to describe drought scenarios: the time horizon of the analysis, the probability of having water shortages and the expected deficit volume. The time horizon depends on the nature of the regulation of the system. For the reasons explained in the Chapter 4 the one year time horizon is chosen. The probability of shortage must reach a balance between the certain damages that will be caused by the implementation of drought measures and the probable future damages that will be avoided by them. Finally, the expected deficit volume will depend on the nature of the demand. These parameter values should be agreed by all stakeholders through a negotiation process that requires the use of water resources simulation models in order to quantify these thresholds. In this work an imposed reduction of demand is proposed to mitigate the effects of droughts. A logical sequence of restrictions on the supply systems would be:

- Irrigation of parks and public gardens and flushing of streets, which can also be met with alternative sources like recycled water. Irrigation could simply consider historical gardens or tree species of special interest.
- Ban of nonessential uses, such as filling swimming pools, ornamental fountains, washing cars, irrigation of private gardens.
- Restrictions on industries, ensuring the availability of alternative sources of inferior quality.
- Limitations to urban systems based on voluntary restrictions, reached through information campaigns.
- Partial cuts to urban supply system.

5.4 OPERATIONAL RULES UNDER DROUGHT CONDITIONS

5.4.1 Operational rules individuation

The operational implementation of drought mitigation measures requires a connection between the system of drought indicators and selected rules. A set of measures associated to a drought scenario are activated when a given drought indicator reaches a predefined level. The correct definition of critical thresholds implies to reach a balance between the frequency of declaration of drought scenarios and the effectiveness of the application of measures. If drought scenarios are declared too early, users are frequently exposed to unnecessary restrictions. If the declaration of drought scenarios is delayed, it may be too late for the measures to be effective. Computer modelling is an essential tool to analyse the problem and to find a consensus among users by testing different options.

The objective of the analysis is to define the thresholds for the declaration of the pre-alert, alert and emergency scenarios. Since future reservoir inflows are uncertain, these thresholds should be formulated in probabilistic terms (Steinemann, 2003). Most of the methodologies applied in practice are based on the supply side: they use hydrological indicators, and thresholds are defined by comparing indicator values to some historic reference values. In their analysis, they do not account for the characteristics of the water supply system, the nature or vulnerability of demands, or the social or institutional constraints in water management. In the methodology proposed in this work, thresholds are defined as the available storage in the system, S, that is required to satisfy a fraction, f, of the demand in one year time horizon, with a given probability, *p*. Values of *f* and *p* are model parameters that should be fixed though discussion with stakeholders. They depend on several factors: the type of the demand in the system, the reliability of the current water supply system, the alternative management strategies that can be applied during droughts, and the vulnerability of the demand to deficits of a certain magnitude.

The group of graphs in Fig. 4.12 is fundamental to develop reservoir operation policies under drought condition. Each of the represented curves can be utilized as threshold level for the pre-alert, alert or emergency scenario and to trigger management actions, such as demand reduction. A new graph (Fig. 5.1) is built to represent all the curves that are evaluated in a single graph.

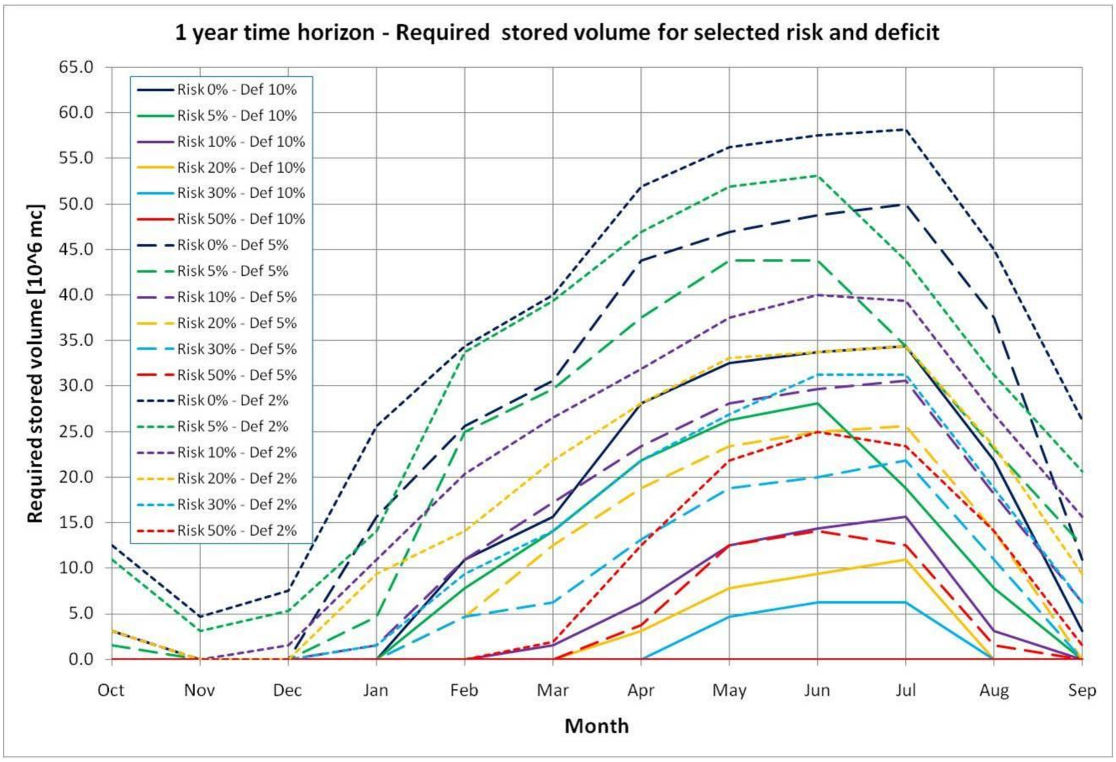


Figure 5.1 Required reservoir volumes in different months for three considered deficit levels (2%, 5%, and 10%) and six risk of failure levels (0%, 5%, 10%, 20%, 30%, and 50%)

Definition of the operation rules implies to select the threshold values and to define the required demand reduction at every stage. Values that prevent catastrophic shortages but at the same time do not cause unnecessary restrictions have to be defined. With the optimization process the threshold levels and the rules to mitigate the drought are evaluated.

The threshold values and the rules to be imposed on the system for the drought mitigation are optimized through simulations of the water supply system under drought management rules for two long term conditions. The system is evaluated firstly with the infrastructures and the demands of 2005 and with the inflows and precipitation of the period 1975-2005. To adapt to current requirements imposed by the Water Framework Directive the ecological streamflow requirements have been assigned a higher priority of allocation than the demand centres.

A second state, considering a progressive reduction of Arno River stream flow of 2.5‰ every year that entails a reduction of the 8.16% in last year of simulation, is evaluated to verify the performance of the operating rules in a future situation in which there could be a reduction of streamflow due to demands increasing and climate change effects. Daily mean discharge of Arno River, according to some studies of Arno River Basin authority (2008), has been reduced on average of 30% in the last 50 years.

The objective of the optimization is to minimize the deviation of each supply from the respective demand targets while the system is operating under drought management rules. The objective function *ZF* is defined as an aggregate of the squared ratio between d, deficit on water supply, and *Su*, designed water supply, for all the demands *i* and all the time steps *t*:

$$ZF = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(\frac{d_{ti}}{Su_{ti}}\times 100\right)^2 \qquad \text{with } i=1,2 \qquad t=1,2\ldots T \tag{5.1}$$

To let the optimization procedure seek the solution which reduces the risk of extreme supply shortages, this function penalizes a large deficit more than a number of smaller deficits amounting to the same volume.

The process uses a trial and error scheme incorporating the concept of dynamic programming approach that converts an n-stage decision problem into a series of n single-stage decision problems.. The optimal policy can be determined proceeding stage by stage and by considering only decisions at the current stage in conjunction with the optimal policy for the previous stage. The sequential nature of this approach makes it suitable for the determination of reservoir operating rules. The objective function is minimized over the decision variables:

a) Storage volume thresholds: (V_1, V_2, V_3)

b) Supply restrictions: (r_1, r_2, r_3)

with V_1 and r_1 relative to pre alert state, V_2 and r_2 relative to alert state and V_3 and r_3 relative to emergency state. Given the inflows and demand data and the spill (I_t, S_t, SP_t) with t = 1, 2, ...T, the following operating rules are applied to the reservoir:

$$\begin{aligned}
&\textit{if } V_{t-1}+I_t > V_1 \textit{ then } D_t = 0\,;\, V_t = V_{t-1}+I_t-Su_t\,;\, \textit{if } V_t > V_{\max} \textit{ then } V_t = V_{\max}-SP_t\\
&\textit{else if } \quad V_{t-1}+I_t > V_2 \quad \textit{then} \quad D_t = r_1 Su_t\,;\, V_t = V_{t-1}+I_t-(1-r_1)Su_t\\
&\textit{else if } \quad V_{t-1}+I_t > V_3 \quad \textit{then} \quad D_t = r_2 Su_t\,;\, V_t = V_{t-1}+I_t-(1-r_2)Su_t\\
&\textit{else if } V_{t-1}+I_t > (1-r_3)Su_t \quad \textit{then} \quad D_t = r_3 Su_t\,;\, V_t = V_{t-1}+I_t-(1-r_3)Su_t\\
&\textit{else} \quad D_t = Su_t - V_{t-1} - I_t\,;\, V_t = 0
\end{aligned} \tag{5.2}$$

System performance under several combinations of threshold values *V* and several values of demand restriction *r* for each drought condition are evaluated through long term simulations. Three groups of curves, taken from the deficit-risk curves (Fig. 5.1) are evaluated. Each group has different threshold levels for alert, pre alert and emergency scenario that range from the curve risk 0% and deficit 2% to the curve risk 50% and deficit 5%. In each group the curves for the three levels are dissimilar enough to permit a real differentiation of the rules related to each level. Curves that are higher (needing high stored volumes) are considered in the first group, median curves are considered in the second group while in the last one lower curves (needing low stored volumes) are considered. All the curves (shown in Tab. 5.1) proposed for each group are combined to find the minimum value of the optimization function.

Table 5.1 Threshold levels evaluated for the optimization, subdivided into groups.

State of the system	Group 1	Group 2	Group 3
pre alert	risk 0% - deficit 2%	risk 5% - deficit 2%	risk 10% - deficit 2% risk 20% - deficit 2%
alert	risk 10% - deficit 2%	risk 5% - deficit 5% risk 10% - deficit 5%	risk 30% - deficit 5% risk 10% - deficit 10%
emergency	risk 20% - deficit 5% risk 10% - deficit 10%	risk 20% - deficit 5% risk 30% - deficit 5%	risk 20% - deficit 10% risk 50% - deficit 5%

For each group a first iterative optimization process is carried out. For each stage a set of candidate threshold values, taken from the previous groups is considered. For each candidate value a demand restrictions in (r_{min}-r_{max}) is considered. Mitigation measures modify significantly the cumulative objective function. Without any measure the cumulative objective function has step behaviour. Each month with a failure in the water supply system, produces a step. The various groups of management rules have the effect to reduce the main steps, to erase the lower one and to distribute part of the deficit in the "plain" parts. The results are curves with a distributed increase and little steps. The rules that perform best are the ones that are able to smooth considerably the steps and to reduce significantly the curves values.

Simulations through WEAP software are repeated for different values and restrictions. WEAP is able to simulate the effects of various demand side management (DSM) strategies for reducing demand. With a programme in WEAP programming language the different demand reduction are performed once specific reservoir levels are reached at the end of the previous month. A hypothesized value of demand restriction is evaluated and then the value of the objective function for immediately higher and lower values is found. The objective function has a parabolic behaviour near the minimum (Fig. 5.2), so that it is possible, with an iterative process, to find the minimum value.

At the first attempt the hypothesized values of imposed reduction have a precision of 0.1. Once that the optimum value is found for a stage, the process is repeated for a different state, since that the value of restrictions of each stage influence the optimum values of the others. Therefore the process starts finding the optimum for the alert curve, then for the pre-alert one, then for the alert one, then for the emergency. Then another loop is performed. Since the obtained values for group 1 with these first attempts of optimization are lower than the ones of the other two groups, this group is not considered further. Several combinations of curves of the other two groups are evaluated. The pair (V_k, r_k) which minimizes objective function is chosen. At this second level the hypothesized values of imposed reduction have a precision of 0.01.

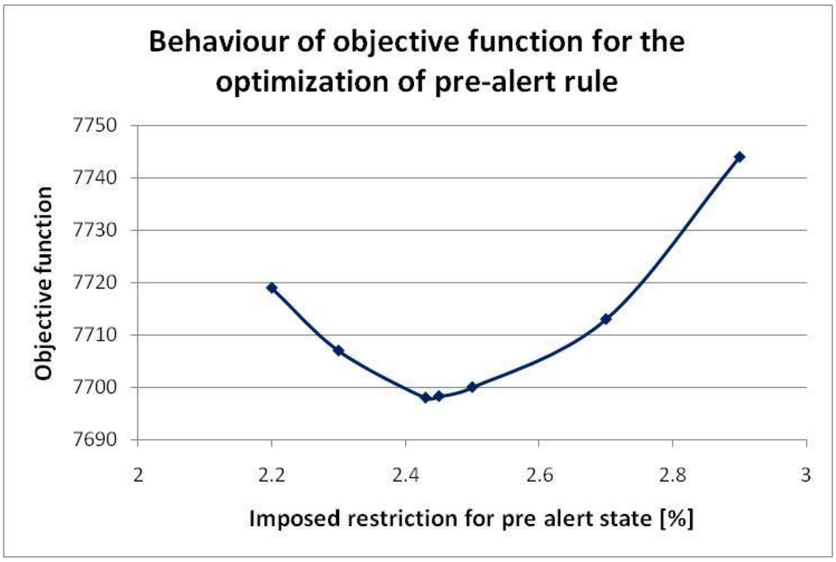


Figure 5.2 Behaviour of the objective function for the optimization of pre-alert rule.

In Fig. 5.3 is possible to see the effects of the different groups of mitigation measures on the cumulative objective function on reduced flow state, time span 1970-2005. Without any measure the cumulative objective function has a step behaviour. The various groups of management rules have the effect to reduce the main steps and to distribute part of the deficit in the "plain" parts. It is clear that the optimized curves, belonging to the third group, are the ones that reduce the most the objective function.

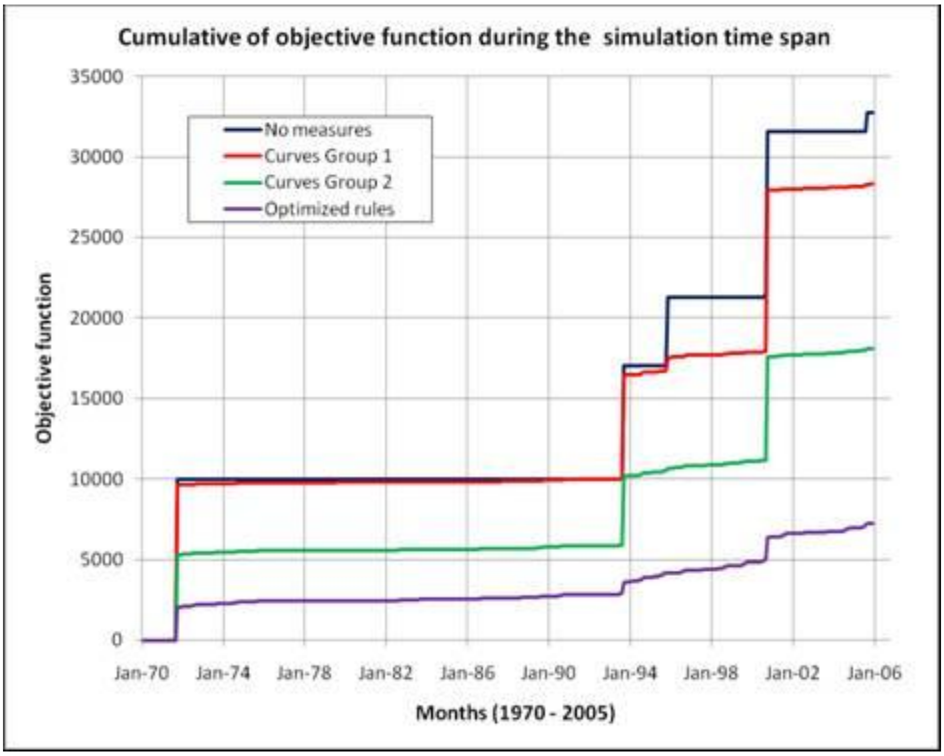


Figure 5.3 Effects of different drought mitigation measures on reduced flow state, time span 1970-2005: comparison between the situation without rules (above) and with rules (below).

5.4.2 Operational rules effects

The threshold levels (Fig. 5.4) are calibrated with simulations for the heavier state. In fact they are optimized for the state with the reduced inflows in the system due to the reduction of Arno River flows. In Tab. 5.2, as in the following graph, the values of the threshold levels and of the demand reductions are presented. The threshold levels are rather high compared to the demand reduction. This is caused by the fact that the conditions on the Arno flow reduction state are heavier than the ones considered in the short term simulation.

Table 5.2 Management parameters: threshold levels and related imposed demand reduction.

State of the system	Threshold levels	Demand reduction (%)
pre alert	risk 5% - deficit 2%	2.43
alert	risk 5% - deficit 5%	5.18
emergency	risk 20% - deficit 5%	8.40

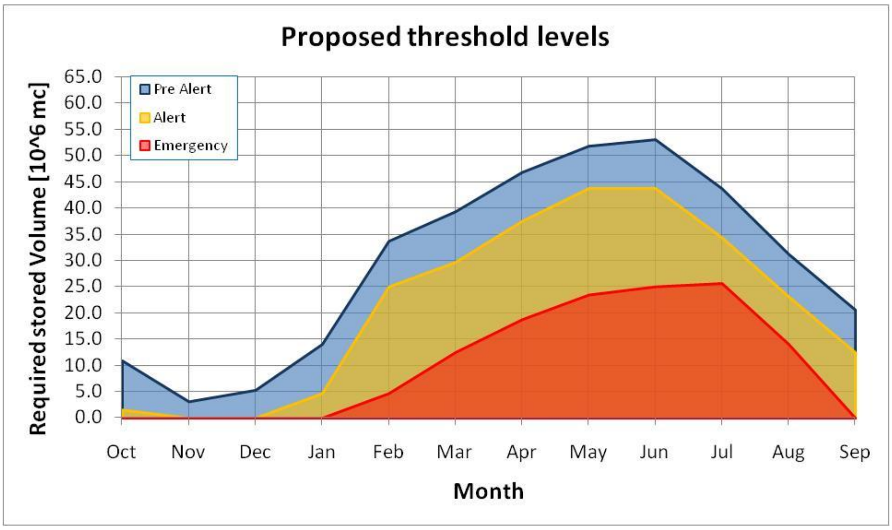
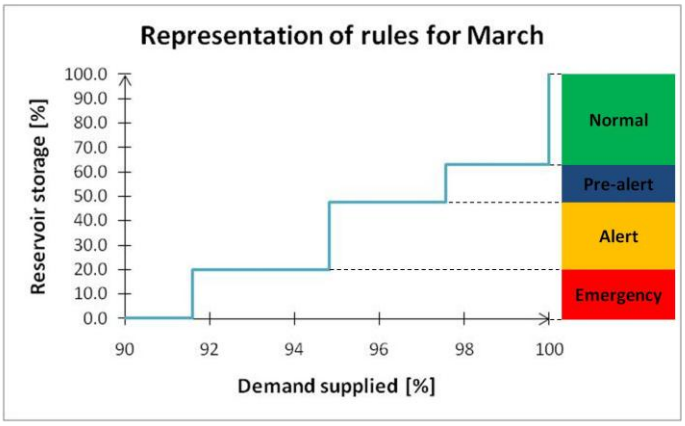


Figure 5.4 Proposed monthly reservoir volumes as threshold levels for the different drought management scenarios.

The pre-alert thresholds require that in late spring and at the beginning of summer the reservoir should be quite full in order to minimize the effects of the arid summer months, while in November and December the reservoir can be quite empty. The alert and emergency thresholds require a volume starting respectively on December and January and the maximum volumes respectively on May and July.

In Fig. 5.5 and 5.6 the imposed demand reductions are presented. The demand reductions, related to the respective threshold levels, are shown for two meaningful months, March (Fig. 5.5) and June (Fig. 5.6). While the imposed reductions are constant, the threshold levels vary during the year.

The obtained demand reductions values are near to the ones present in literature (Iglesias et al., 2008). A temporary reduction of the demand may be obtained by public campaigns for water saving, restriction of some urban water use (e.g. car washing or gardening) and pricing mechanisms.



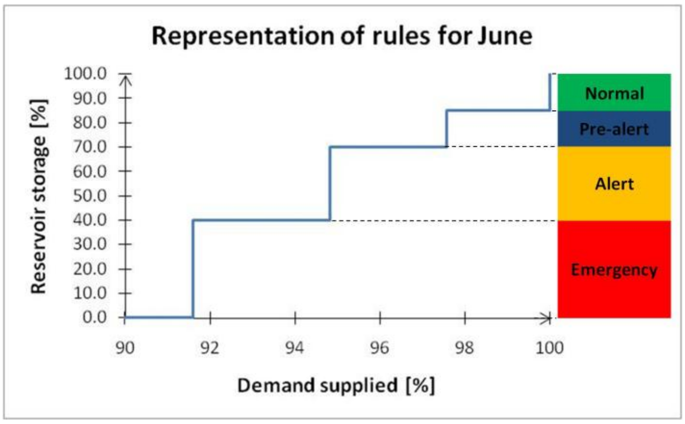


Figure 5.5 Representation of the rules for two significant months: rules for March (above) and June (below).

In Fig. 5.7 the effects of operating the water supply system under drought management rules are shown. Analysing the state with reduced flows, six severe droughts are present and the effects of three of them are completely mitigated. Mitigation for the other three cases is not possible because of the celerity with which the system enters in the alert and emergency scenarios in one case and because of the long duration of the drought in the other two cases.

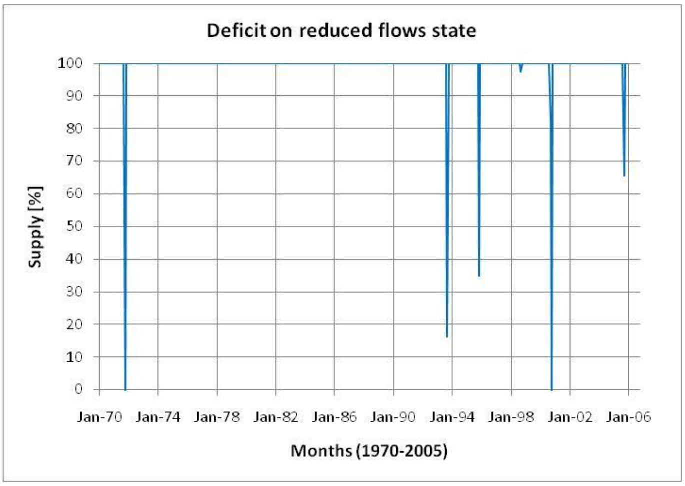


Figure 5.6A Effects of drought mitigation measures, reduced flow state, time span 1970-2005: comparison between the situation without rules (A) and with rules (B).

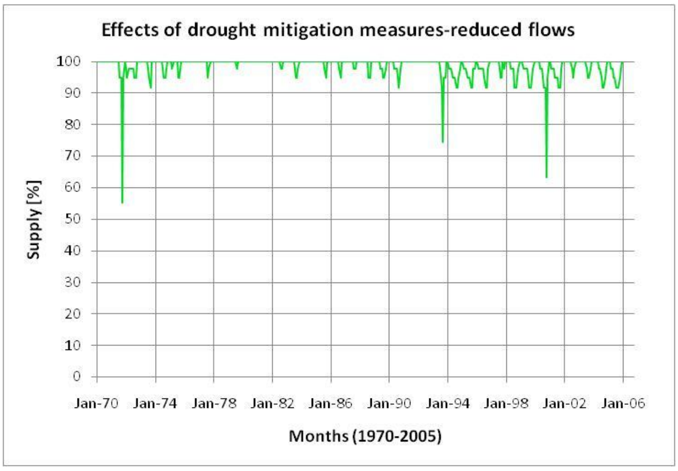
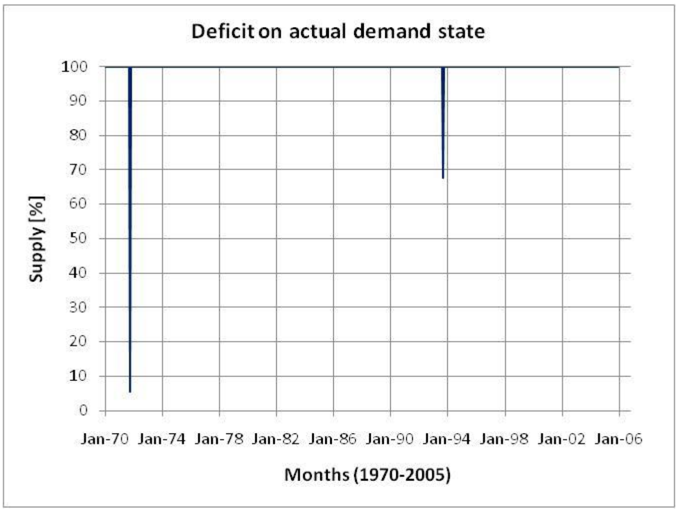


Figure 5.6 B Effects of drought mitigation measures, reduced flow state, time span 1970-2005: comparison between the situation without rules (A) and with rules (B).

The same threshold levels and demand reductions are applied to the normal state to verify the efficiency of the proposed rules. The effects on the actual setting are shown in Fig. 5.8.



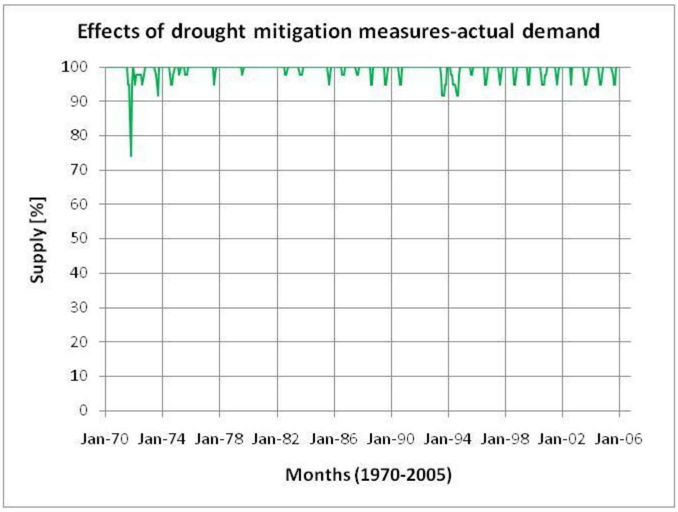


Figure 5.7 Effects of drought mitigation measures, actual demand state, time span 1970-2005: comparison between the situation without rules (above) and with rules (below).

There is a deficit in the event on 1971, but its effects are reduced of about 70%. The procedure is not able to avoid completely the effect of this drought because of the celerity with which the system enters in the alert and emergency scenarios. The system enters more than 20 times in the pre alert scenario and 4 times in the emergency one. With these simulations a pre-alert state evolves into an alert or emergency state about the 72% of times. The 77% of times the system recovers from an alert state without reaching the emergency level. Therefore only the 22% of times that the system enters in the pre-alert state it reaches an emergency state. The system enters in the pre-alert state on August and September about the 60% of the times and in the alert state about the 20% of times.

5.4.3 Operational rules verification: synthetic streamflow generation

The natural flow at a point of observation on a river is primarily function of the effective rainfall during a previous period; effective rainfall is that part which contributes directly to surface run-off. The form of the function and the extent of the period depend on the type of terrain, its area and water courses and the rates and areal distribution of rainfall input. Catchment retention, losses through evaporation and transpiration from plants, and infiltration into the ground, all control the amount of rainfall which contributes to river flow as surface run-off. In addition, the flow may be supplemented by underground sources, catchment storage and melting snow. As for rainfall itself, present knowledge of storm mechanisms and meteorological processes means that its prediction beyond a limited period is rather speculative. In addition to variance in the amount of precipitation and its spatial and temporal non-uniformity, there are seasonal and diurnal variations in evaporation, and sporadic fluctuations in groundwater flows. Infiltration losses depend on soil properties, as well as forest cover, current and antecedent precipitation and other factors. Natural erosional processes cause variation in sediment loads which alter the hydraulic character of rivers. Deforestation, urbanization, flow diversions and other forms of human intervention give rise to changes in the relationship between catchment run-off and flow. The combination of all these factors make river flow a highly complex process, and one which can to good effect be treated stochastically.

Hydrologic records of observed flow data vary in length from a few years to 50 years or more. Although long records are rare even in the most advanced countries, a hydrologist could have for analysis a 50-year length of flows for a river from his area of interest. This river might, however, have existed for many thousands and perhaps millions of years, and one could easily believe that the river exhibits much larger pseudo-cyclic changes than the 50-year maximum allowed for by the historical record. Such effects are probably caused by variations in the energy radiated by the sun, or atmospheric circulations or concentrations of dioxide and dust in the air. The stance taken by the hydrologist, however, to these phenomena, is usually that the relevant time span is the economic life of the engineering system, and that during this interval the flow is stationary; it is then sensible to simulate likely future flow conditions. Whether or not this position is justified is not always obvious. The overall purpose of

the analysis may be to determine the size and future performance of a storage reservoir to be constructed near the flow measurement site (Lawrance and Kottegoda, 1977).
Synthetic sequences of flows are produced to evaluate the performance of the system. The idea is to test it under a variety of conditions, and with longer sequences of flows than historically available. The implication is that long sequences will contain more extreme events than observed and thus be a more stringent test of the system. It is required that the synthetic flows should have statistical properties which are indistinguishable from the historical flow. This is taken to mean that the generated flows should have some population means, variances and correlations, or other simple properties, which are preserved in exact agreement with their historical values.
Several models have been developed with the aim of preserving one or more characteristics of investigated series. They usually differ according to the time scale of the analysis, since for instance in the case of data aggregated at sub-yearly time scale the seasonality of the statistics must be taken into account. Accordingly, models can be stationary or periodic. Models can also be classified according to whether the interest lies in modelling one series or several series jointly preserving the cross correlation (multivariate models). Also, while most models are developed in the normal domain thus requiring a preliminary data transformation, in the case of non-normal observations some models are able to generate directly skewed data (Salas, 1993).
The hydrologists' usual approach is to attempt removal of the seasonality by adjusting each observation for its appropriate mean and variance, these latter quantities being estimated from the data. This is known as pre-whitening. The resulting series is said to be deseasonalized and assumed to be stationary; it is then modelled by a stationary stochastic model which is finally de-whitened into a seasonal model. These models were heavily criticized by the statistics. For this reason in this work a statistical approach is used: the ARMA model.
Following Lawrance and Kottegoda (1977) the Markov or first-order auto-regressive (ARMA) model, applied to stationary and standardized annual or monthly series, is used to generate synthetic flows. If μ_τ and σ_τ^2 are the seasonal means and variances of the flows $\{X_t\}$, ρ is the lag one correlation and $X_{t,\tau}$ denotes that X_t refers to month τ then the model takes the form:

$$\frac{\mathrm{X}_{t+1,\tau+1}-\mu_{\tau+1}}{\sigma_{\tau+1}}=\rho\frac{\mathrm{X}_{t,\tau}-\mu_\tau}{\sigma_\tau}+(1-\rho^2)^{1/2}\varepsilon_{t+1} \quad t=0, \pm1, \pm2,\ldots \tag{5.3}$$

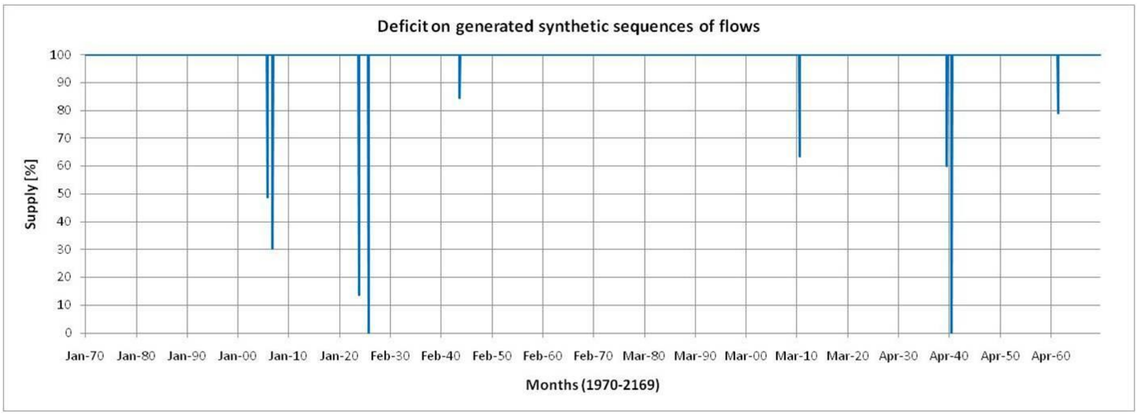
Hence, for n years of monthly data, τ = 1, 2, 12 and t = 1, 2, 12n.
Streamflow series on nearby sites are usually correlated. Correlation means that the flows in the same time period are correlated. The lag zero cross correlation between two random variables X_i and X_h is defined as:

$$cr_{i,h}=\frac{\sum_{j=1}^{n}\left(\mathrm{X}_{\mathrm{i,j}}-\mu_i\right)\left(\mathrm{X}_{\mathrm{h,j}}-\mu_h\right)}{(n-1)\ \sigma_i\sigma_h} \tag{5.4}$$

where n is the total number of pairs of observations on X_i and X_h, σ_i^2 and σ_h^2 and μ_i and μ_h are respectively the variance and the mean of the observation of the two variables. The cr coefficient between streamflow data of Nave di Rosano and Fornacina gauge stations is 0.761 and the one between streamflow data of Nave di Rosano and Bilancino gauge stations is 0.616.
A two site generation model that preserves the means, variances, skewness, lag one serial correlation and lag zero cross correlation is used, following Haan (1977). The technique requires that one of the two sites is selected as a key site. Arno streamflow at Nave di Rosano is selected as key site because of the length of this record and because the flows are higher in this site. We will assume that the site i is the key site and site h is subordinated to site i. A sequence of observation is generated for river Arno using the Equation (5.3) and then a cross-correlation model is used to generate values on the sites Fornacina and Bilancino (sites h) based on generated values for Arno river (site i).

$$\mathrm{X}_{\mathrm{h,j}} = \mu_h + r_{i,h}\sigma_h \frac{\mathrm{X}_{\mathrm{i,j}} - \mu_i}{\sigma_i} + \sigma_h (1-r^2)^{1/2} \varepsilon_j \tag{5.5}$$

With this procedure a 200 years sequence of flows is produced for the three inflows entering in the system. In order to verify the efficiency of the proposed rules the synthetic streamflows are supposed entering in the systems in the period 1970-2069. Simulations are performed firstly for the system without any management rule and then with the optimized threshold levels and demand reductions. The results are shown in Fig. 5.9. Without management rules 9 months with a failure are present: 3 of them have a severe deficit (more than 80%), two have a high deficit (more than 50%) and 4 have a medium deficit. The drought mitigation measures alleviate the effects of the medium deficits, even without enter in an emergency state in two events. The deficit of 2005 and 2006 are reduced of about 40%. The procedure is not able to avoid completely the effect of this drought because of the celerity with which the system enters in the emergency scenario, in the first case without passing through the alert scenario. The deficit of 2024 and 2026 are reduced of about 60% even if the procedure is more efficient on the second event. The deficit of 2141 is reduced more than the 70%. The system enters 50 times in the pre alert scenario and 10 times in the emergency one. With these simulations a pre-alert state evolves into an alert or emergency state about the 46% of times. The 80% of times the system recovers from an alert state without reaching the emergency level. Only the 20% of times that the system enters in the pre-alert state it reaches an emergency state. In the month of August the system is in pre alert ore more severe state the 56% of times and in alert or emergency the 22% of times.



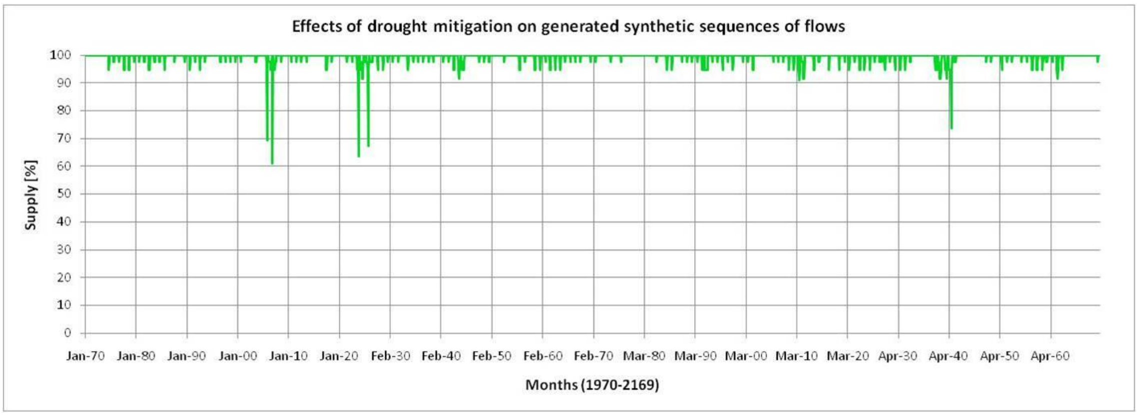


Figure 5.8 Effects of drought mitigation measures on generated synthetic sequences of flows, time span 1970-2169: comparison between the situation without rules (above) and with rules (below).

The effects of the mitigation measures are evaluated even using some performance indices. Performance criteria capture particular aspects of possible system performance. They are especially important during periods of drought, peak demands, or extreme weather and they were developed by Hashimoto et al. (1982). The proposed indices are called reliability, resiliency, and vulnerability. System performances can be described from three different viewpoints: how often the system fails (reliability), how quickly the system returns to a satisfactory state once a failure has occurred (resiliency), and how significant the likely consequences of failure may be (vulnerability).

The reliability of a system can be described by the frequency or probability that a system is in a satisfactory state S:

$$\alpha = prob\ [X_t \in S] \tag{5.6}$$

That in the application to water supply systems with a discrete time step become:

$$\alpha = \frac{m_{tot} - m_{fail}}{m_{tot}} \tag{5.7}$$

with m_{tot} number of total months and m_{fail} number of month with a failure.

Resiliency describes how quickly a system is likely to recover or bounce back from failure once failure has occurred. If failures are prolonged events and system recovery is slow, this may have serious implications for system design. The resiliency of a system simulated with a discrete time step is:

$$\gamma = \frac{1}{T_f} = \frac{1}{\dfrac{m_{fail}}{B}} = \frac{B}{m_{fail}} \tag{5.8}$$

where T_f is the length of time a system's output remains unsatisfactory after a failure, m_{fail} is the total time in failure and B is the number of times the process went into failure. Vulnerability refers to the likely magnitude of a failure, if one occurs. Even when the probability of failure is small, attention should be paid to the possible consequences of failure. To construct a quantitative indicator of system vulnerability to severe failure to each discrete failure state x_j a numerical indicator of the severity of that state, denoted s_j, is assigned. Furthermore let e_j be the probability that x_j, corresponding to s_j, is the worst failure that occurs in a period of drought. A reasonable metric for overall system vulnerability would be the expected maximum severity of a stay into the set of unsatisfactory states.

$$\upsilon = \sum_j s_j e_j \tag{5.9}$$

The proposed mitigation measures attempt to make the consequences of failure less severe and more acceptable, than trying to eliminate the possibility of failure. In fact, the system is forced to cope with more small failure to prevent a catastrophic one. The values of the Hashimoto indices are calculated firstly using as satisfactory state the one without failure. Than they are calculated, following an untraditional approach, considering satisfactory state the one with failure minor of 10% of demands. This second approach, proposed even in Houck and Datta (1981), let to consider only the higher values of failures. In Tab. 5.3 the results for the different states are shown. In order to decrease the vulnerability of the system (that is halved in the first state and reduced of 80% circa in the second one), a decrease of the reliability and resiliency is accepted. Value of resiliency decrease significantly because in the states without rules there are sudden failure of big amounts, while the goal of the mitigation procedure is to have several controlled failures in advance in order to avoid a disastrous failure during the drought period. On the contrary if only the failure higher of 10% of demands are considered unsatisfactory situation resiliency as well as reliability are increasing for all the three states, while vulnerability is decreasing in the meanwhile. This second way to apply the Hashimoto indices underlines the good functionality of the proposed mitigation rules.

Table 5.3 Reliability, resiliency and vulnerability values for the state A (actual inflows) and the state B (reduced inflows) with and without managing rules for drought mitigation.

State		**Reliabil α**	**Resilien γ**	**Vulnerab v**	**Reliabil α - 10%**	**Resilien γ - 10%**	**Vulnerab v - 10%**
State A	no rules	0.995	1.000	1.270	0.995	1.000	1.270
	with rules	0.833	0.431	0.674	0.998	1.000	0.258
State B	no rules	0.984	0.857	3.354	0.986	0.833	3.310
	with rules	0.748	0.275	0.713	0.991	1.000	1.080
Generated streamflow	no rules	0.996	1.000	5.199	0.996	1.000	5.199
	with rules	0.863	0.418	0.832	0.998	1.000	1.85

CHAPTER 6 – SYNOPSIS

6.1 SUMMARY

Drought is the most complex and least understood of all natural hazards and at the same time affects more people than all the other natural hazards. Given projected increases in temperature and uncertainties regarding the amount, distribution and intensity of precipitation, the frequency, severity and duration of drought may increase in the future.

In the present dissertation an original procedure for drought risk identification and assessment, in order to develop mitigation measures, is presented. The procedure of risk assessment conceived within the Graduate College GRK 802 in "Mitigation of risk due to natural hazards on structures and infrastructures" is applied to drought risk and some novel parts are proposed for each component.

The first phase in risk management chain is risk identification. It is difficult to identify when the drought begins. Likewise it is difficult to determine when a drought is over and on what criteria its magnitude should be determined. Drought indices, particularly the meteorological ones, are developed to identify the onset and the persistency of droughts, especially in natural systems. The hydrological indices, which identified the hydrological drought, the ones that more affect human systems and activities, are based on streamflow data. For sites where these data are unavailable, a diffuse problem in the real world, hydrological regionalisation techniques can be used to infer them from other catchments where streamflow data have been collected. The regional analysis improves the capability to predict the water flow regime at gauged sites with short time series, reducing the uncertainties and moreover allows the estimation of the discharge properties at ungauged sites. An original method of low flow indices regionalisation is proposed. Two low flow indices are chosen, the Q70, the 70 percentile of flow duration curve, and the Q(7,2), the 10-year annual minimum 7-day discharge. The study is applied to Tuscany region gauge stations. A preliminary work on the data record of Servizio Idrologico Regionale Toscano (Regional Hydrologic Service of Tuscany) is done in order to have a consistent dataset. Some existing instruments used for flood regionalisation are used in an innovative way. In particular the area of study is subdivided into homogeneous sub-regions using the L-moments. Three different subdivisions are tested. A unique region is evaluated, but it is not sufficiently homogeneous. The subdivision into three different sub-regions, following previous studies on rainfall extreme values gives some homogeneity, but some stations still presented high values of discordancy. Finally a new subdivision with 5 sub-regions was proposed, splitting the central and the northern regions of the three previous subdivisions, as well as following the main hydrological watersheds. This subdivision reaches a good degree of homogeneity. Low flow indices at ungauged basins are evaluated through interpolation techniques and Multivariate Analysis. Inverse Weighted

Distance and Universal Kriging are assessed. Furthermore a novel Multivariate Analysis is carried out and a relation connecting low flow indices and geomorphoclimatic characteristics is found.
The results are valuated using the jackknife method and calculating the RMSE – Root Mean Square Error for the different techniques and the different subdivisions. For IDW the RMSE values confirm the good properties of homogeneity of the final subdivision for three sub-regions (South, Centre East, and Centre West) while for other two (North East and North West) the results are not the expected ones. Ordinary Kriging performs better, especially in the North East and North West sub-regions. The Multivariate Analysis is the estimation method that performs best. It is able to solve the problems in the two northern regions: in these regions the considered low flows indices present a high variability that can be explained taking into account the geomorphoclimatic characteristics.
Prolonged absence of precipitation, soil moisture deficit and decreasing in river flows do not necessarily mean scarcity in an artificial water resources system. Water can in fact, be supplied from natural and artificial reservoirs: aquifers and regulated dams can sustain water demands during period of droughts. Shortage risk depends on demand fluctuation and on the actions carried out in order to reduce drought effects. For those reasons, dynamic indicators, relating resources and demand, are required in order to identify the probability of occurrence of situations with a certain risk of water shortages. A procedure for long term risk assessment is proposed to evaluate the capability of the system to react to severe drought events and to help to develop reservoir management operation rules under drought conditions. With this procedure it is possible to evaluate the probability to have a certain degree of failure in a water supply system given the volumes stored in the reservoirs at the beginning of the month. Monte Carlo simulations are performed using the software package WEAP. A model of the Florence urban area water supply system is built and the probability to have definite degree of shortage is evaluated. Required volumes to avoid the risk to have certain failures are found month by month. Some probability curves are built to show the results: required volumes are maximum in summer and minimum in winter, in accordance with hydrologic regime.
Curves representing these volumes are the basis of the proposed methodology to develop reservoir operation policies under drought condition. Some proactive measures, affecting the demand, are suggested. Four scenarios (normal, pre-alert, alert and emergency) associated with different levels of severity of drought can be defined. Definition of the operation rules implies to select the threshold values and to define the required demand reduction at every stage. Values that prevent catastrophic shortages but at the same time do not cause unnecessary restrictions are defined. A novel optimization of drought mitigation rules is proposed. Thresholds levels for the declaration of the pre-alert, alert and emergency scenarios are identified. The threshold values, as well as the related management rules, are delineated considering the probability to satisfy a given fraction of the demand in a certain time horizon. They are calibrated with an optimization procedure, which

tends to minimize the water shortages, especially the most severe. The procedure is evaluated with a long term simulation and verified with long term simulations using generated synthetic time inflows. Once proper values for the three threshold levels and the related demand reduction are defined, the proposed mitigation rules are able to reduce the effects of most severe droughts.

6.2 CONCLUSIONS AND OUTLOOK FOR FUTURE RESEARCH

The research carried out in the framework of doctoral activities attempts to improve a novel procedure for drought risk identification and assessment in order to develop mitigation measures.

A new method of low flow indices regionalisation is proposed and evaluated. In particular a procedure to evaluate low flow indices in ungauged basins is identified using a regional regression approach.

The multivariate analysis is the estimation method of low flows in ungauged basins that performs best. The IDW and the Ordinary Kriging have given results with a high bias: these techniques are not very suitable for the streamflow assessment in ungauged sites. Other interpolation methods such as the Top-Kriging or the Physiographical Spaced Based Interpolation-PSBI have to be taken into account to reach more exact results

An improvement of the proposed regional regression approach is possible considering a bigger variety of geomorphoclimatic variables and taking into account not only their main values into the catchment area but even their variability in each sub-basin.

An original procedure for drought risk assessment is also proposed. The probability to have definite degree of shortage in the water supply system is evaluated as a function of the volume stored in the reservoir. Some probability curves are built to show the results.

A procedure for the mitigation of drought risk is also proposed, based on the results of the risk assessment. Some proactive measures, affecting the demand, are suggested. Four scenarios (normal, pre-alert, alert and emergency) associated with different levels of severity of drought are defined and mitigation rules able to reduce the effects of most severe droughts are connected to each scenario. The procedure can be applied to all the water supply systems with the resource coming from water bodies regulated with a reservoir or a system of reservoirs, once that their peculiarities are taken into account.The risk assessment procedure can be further developed considering several water uses in competition between them. Not only the municipal demands and the flow requirements have to be taken into account but even irrigation and industrial demands.

REFERENCES

AdB – Autorità di Bacino del Fiume Arno (Arno River Basin Authority) (2001) *Bilancio idrogeologico nel bacino dell'Arno (Arno river basin hydrogeological model)*. Firenze, Italy. 257 pp.

AdB – Autorità di Bacino del Fiume Arno (Arno River Basin Authority) (2008) *Piano di Bacino, Stralcio Bilancio Idrico (Basin authority plan: water balance)*. Gazzetta Ufficiale 78.

APAT – Agenzia per le protezione dell'ambiente e per i servizi tecnici (2006) *Linee guida per l'individuazione delle aree soggette a fenomeni di siccità (Guidelines for the individuation of drought prone areas*). Rome. Italy,68 pp.

Alecci S, Reitano B, Rossi G (1986) Evaluation of alternatives in management of water resources systems through performance indices. *Proceedings of the IAHR Intern. Conference on Water Resources Needs and Planning in Drought Prone Areas.*

Alecci S, Cancelliere A, Rossi G (2007) Analisi e monitoraggio della siccità: il ruolo degli indici (Drought analisys and monitoring: the role of indices) . In: Rossi G (Eds.) *Siccità: analisi, monitoraggio e mitigazione. Applicazioni in Sicilia (Drought: analysis., monitoring and mitigation. Applications in region Sicily)*, Nuova Bios, Cosenza, pp 15-48.

Alley W M (1984) The Palmer Drought Severity Index. *Limitations and assumptions. Journal of Climate and Applied Meteorology*. 23: 1100-1109.

Andreu J, Capilla J, Sanchis E (1996) AQUATOOL, a generalized decision-support system for water-resources planning and operational management. *Journal of Hydrology*. 177:269-291.

Arnell N, Gabriele S (1985) Regional flood frequency analysis with the two-component extreme value distribution. An assessment using computer simulation experiments. *Workshop on Combined Efficiency of Direct and Indirect Estimations for Point and Regional Flood Prediction*, Perugia, Italy.

ASCE – American Society of Civil Engineering - Task Committee on Sustainability Criteria (1998) *Sustainability for water resource systems.* ASCE and UNESCO/IHP IV Project M-4.3, Water Resources Planning and Management Division, ASCE, Reston.

Aschwanden H, Kan C (1999) Le débit d'étiage Q347—Etat de la question (The low flow indices Q347 – State of the question). *Communications hydrologiques, 27*. Service Hydrologique et Geologique National, Berne.

Assaf H, van Beek E, Borden C, Gijsbers P, Jolma A, Kaden S, Kaltofen M, Labadie J W, Loucks D P, Quinn D W, Sieber J, Sulis A, Werick W J, Wood D M (2008) Generic simulation models for facilitating stakeholder involvement in water resources planning and management: a comparison, evaluation, and identification of future needs. In: Jakeman A, Voinov A, Rizzoli A E, Chen S (Eds.) *Environmental Modelling, Software and Decision Support (3): The State of the Art and New Perspective*. IDEA Book Series, Elsevier. pp. 229-246.

Bates B C, Kundzewicz Z W, Wu S, Palutikof J P (Eds.) (2008), *Climate Change and Water, Technical Paper* VI, Intergovernmental Panel on Climate Change, Geneva, Switzerland, pp. 210.

Bonaccorso B, Cancelliere A, Di Mauro G, Rossi G (2007) Drought identification and probabilistic characterization. In: La Loggia G, Aronica G T, Ciraolo G (Eds.) *Water Resources Assessment under Water Scarcity Scenarios.* Centro Studi Idraulica Urbana, Milano: 1-28.

Brath A, Castellarin A, Montanari A (2003) Assessing the reliability of regional depth-duration-frequency equations for gaged and ungaged sites. Water Resources Research. 39 (12): 1-11.

Breiman L, Friedman J H, Olshen R, Stone C J (1984) *Classification and Regression Trees*. Wadsworth International Group, Belmont, California.

Briceño S. (2007) *Report to the United Nations General Assembly 61st session*. UN printing, New York, 21 pp.

Cai X, McKinney D C, Lasdon L S (2002) A framework for sustainability analysis in water resources management and application to the Syr Darya Basin. *Water Resources Research.* 38(6): 1085-1094.

Caissie D, El-Jabi N (2003) Instream flow assessment: from holistic approaches to habitat modelling. *Canadian Water Resources Journal.* 28: 173-184.

Calatrava J, Garrido A (2005) Modeling water markets under uncertain water supply. *European review of Agricultural Economics.* 32: 119-142.

Cancelliere A, Ancarani A, Rossi G (1998) Susceptibility of water supply reservoirs to drought conditions. *Journal of hydrologic engineering.* 3: 140–148.

Cancelliere A, Di Mauro G, Bonaccorso B, Rossi G (2007) Drought forecasting using the Standardized Precipitation Index. *Water Resources Management*. 21:801–819.

Cañón J, González J, Valdés J (2009) Reservoir Operation and Water Allocation to Mitigate Drought Effects in Crops: A Multilevel Optimization Using the Drought Frequency Index. *Journal of Water Research.* 135(6): 458-465.

Caporali E, Cavigli E, Petrucci A(2008) The index rainfall in the regional frequency analysis of extreme events in Tuscany (Italy). *Environmetrics*. 19: 714-724.

Caporali E, Tartaglia V (2000) Multivariate analysis of rainfall extreme values. *Proceedings of the 2rd EGS Plinius Conference on Mediterranean Storms – Siena, Italy, p*p 13.

Castellarin A, Camorani G, Brath A (2007) Predicting annual and long-term flow-duration curves in ungauged basins. *Advances in Water Resources*. 30: 937–953.

Castellarin A, Galeati G, Brandimarte L, Montanari A, Brath A (2004) Regional flow-duration curves: reliability for ungauged basins. *Advances in Water Resources.* 27: 953–965.

Castiglioni S, Castellarin A, Montanari A (2008) Stima delle portate di magra in siti non strumentati mediante tecniche di interpolazione spaziale (Low flow estimation in ungauged sites through spatial interpolation techniques). *Proceedings of 31° Convegno Nazionale di Idraulica e Costruzioni Idrauliche Perugia, 9-12 settembre 2008*. 8 pp.

Cate F H (1994) *The media and the disaster reduction*. In: Cate F H (Eds) Harnessing the power of communications to avert disasters and save lives, Washington, D.C.: The Annenberg Washington Program in Communications Policy Studies of Northwestern University.

Chang F J, Chen L, Chang L (2005) Optimizing the reservoir operating rule curves by genetic algorithms. *Hydrological Processes*. 19: 2277-2289.

Chiang S L, Johnson F W (1976) Low flow criteria for diversions and impoundments. *Journal of the Water Resources Planning and Management Division*. 102: 227-238.

Chokmani K, Ouarda T B M J (2004) Physiographical space-based kriging for regional flood frequency estimation at ungauged sites. *Water Resources Research.* 40: 1–12.

CRED CRUNCH (2006) *Disaster Data: A Balanced Perspective: droughts and famine.* Centre for Research on the Epidemiology of Disasters, Brussels, Belgium, 4 pp.

CRED CRUNCH (2010) *Annual Disaster Statistical Review 2009.* Centre for Research on the Epidemiology of Disasters, Brussels, Belgium, 46 pp.

Commission of the European Communities (2007) Communication from the Commission to the European Parliament and the Council COM/2007/414, *Addressing the challenge of water scarcity and droughts in the European Union*.

Cordova J R, Gonzalez M (1997) Sediment yield in small watersheds based on streamflow and suspended sediment discharge measurements. *Soil Technology*. 11: 57–65.

Cunnanne C (1988) Methods and merits of regional flood frequency. *Journal of Hydrology*. 100: 269-290.

Dalrymple T (1960) Flood frequency analysis. *U.S. Geological Survey Water-Supply Paper* 1543-A, GPO, Washington D.C: 11-51.

Demmke C (2001) *Towards effective environmental regulation: innovative approaches in implementing and enforcing European environmental law and policy*. New York University - School of Law, pp 34.

Dracup J A, Lee K S, Paulson E G (1980) On the definition of droughts. *Water Resources Research*. 16(2): 297-302.

Durrans S R, Tomic S (1996) Regionalisation of low-flow frequency estimates: an Alabama case study. *Water Resources Bulletin*. 32: 23–37.

Edwards D C, McKee T B (1997) Characteristics of 20th century drought in the United States at multiple time scales. *Climatology Report Number 97-2*, Colorado State University, Fort Collins.

Elder K (1995) *Snow distribution in alpine watersheds*. PhD thesis. University of California, Santa Barbara, 309 pp.

European Union (2000) Euro Directive 2000/60/EC, *Establishing a framework for the Community action in the field of water policy*.

Fiorentino M, Gabriele S, Rossi F, Versace P (1987) Hierarchical approach for flood frequency analysis. In *Hydrologic Frequency Modeling*, Singh VP (Eds.) Reidel Publications Company, Boston MA: 35–49.

Fisher S, Palmer R N (1997) Managing water supplies during drought: triggers for operational responses. *Water Resources Update*. 3(108): 14–31.

Fleig A K, Tallaksen L M, Hisdal H, Demuth S (2006) A global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences*. 10: 535–552.

Foster H A (1934) Duration curves. *Trans ASCE*. 99: 1213–1267.

Gabriele S, Arnell N (1991) A hierarchical approach to regional flood frequency analysis. *Water Resources Research* 27(6): 1281– 1289.

Garrote L, Iglesias A, Flores F (2008) Development of drought management plans in Spain. In: Iglesias A, Cancelliere A, Wilhite D A, Garrote L, Cubillo F (Eds.) *Coping with drought risk in agriculture and water supply systems*. Springer, Netherlands, pp 175-184.

Garrote L, Martin Carrasco F, Flores F, Iglesias A (2007) Linking drought indicators to policy actions in the Tagus Basin drought management plan. *Water Resources Management*. 21: 873–882.

Gibbs W J and Maher J V (1967) Rainfall deciles as drought indicators. *Bureau of Meteorology Bulletin no. 48*. Commonwealth of Australia, Melbourne.

Gottschalk L, Tallaksen L M, Perzynab G (1997) Derivation of low flow distribution functions using recession curves. *Journal of Hydrology*. 194: 239–262.

Gonzalez J, Valdes J B (2008) A regional monthly precipitation simulation model based on an L-moment smoothed statistical regionalisation approach. *Journal of Hydrology*. 348: 27– 39.

Greenwood J A, Landwahr J M, Matalas N C, Wallis J R (1979) Probability weighted moments: definition and relation to parameters of several distributions expressible in inverse form. *Water Resources Research.* 15: 1049–1054.

Greis N P, Wood E F(1981) Regional flood frequency estimation and network design. *Water Resources Research*, 17(4): 1167-1177.

Grigg N S (1996) Management framework for large-scale water problems. *Journal of Water Resources Planning and Management*. 122(4): 296-300.

Guha-Sapir D, Hargitt D, Hoyois P (2004) *Thirty Years of Natural Disasters 1974-2003*: *The Numbers,* Presses Universitaires de Louvain: Louvain-la-Neuve. 79 pp.

Gustard A, Bullock A, Dixon J M (1992) *Low flow estimation in the United Kingdom* (IH Report No. 108). Institute of Hydrology, Wallingford, Oxon. 88 pp.

Gustard A, Young A, Rees G, Holmes M (2004) Operational hydrology. In: Tallaksen L, van Lanen, H A J (Eds.) *Hydrological drought. Processes and estimation methods for streamflow and groundwater*. Elsevier, Amsterdam, The Netherlands. pp. 455–498.

Guttman N B (1999) Accepting the standardized precipitation index: a calculating algorithm. *Journal of American Water Resources Association*. 35(2): 311–323.

Haan CT (1977) *Statistical Methods in Hydrology*. The Iowa State University press, Ames, Iowa. 378 pp.

Hagman G (1984) *Prevention Better Than Cure: Report on human and natural disasters in the third world*. Swedish Red Cross, Stockholm.

Hammersley J M, Handscomb D C (1975) *Monte Carlo Methods*. London: Methuen. 183 pp.

Hashimoto T, Loucks D P, Stedinger J R (1982) Reliability, resiliency, robustness, and vulnerability criteria for water resource systems performance evaluation**.** *Water Resources Research*, 18(1): 14-20.

Hayes D C (1991) Low-flow characteristics of streams in Virginia. *US Geological Survey Water-Supply Paper*, *File Report 89*: 586–671.

Hayes M J, Svoboda M, Wilhite D A, Vanyarkho O (1999) Monitoring the 1996 drought using the SPI. Bulletin of American Meteorological Society. 80: 429–438.

Hebson C S, Cunnane C (1987) Assessment of use of at-site and regional flood data for flood frequency Estimation. In: V.P. Singh (Ed.), *Hydrologic Frequency Modelling*. Reidel. Dordrecht, pp. 433-448.

Heicher D W (1993) Instream flow needs: biological literature review. *Susquehanna River Basin Commission Publication*. 149: 37 pp.

Heim R R (2002) A review of twentieth- century drought indices used in the United States. *Bulletin of the American Meteorological Society.* 83: 1149–1165.

Hirsch A M (1959), Water legislation in Middle East. *American journal of comparative law*. 8: 168 – 182.

Hisdal H. (2002) Regional aspects of drought. PhD. thesis, No. 221, Faculty of Mathematics and Natural Sciences, University of Oslo, Oslo.

Hisdal H, Clausen B, Gustard A, Peters E, Tallaksen L M (2004) Event Definitions and Indices. In: Tallaksen L M, van Lanen H A J (Eds.) Hydrological Drought – *Processes and estimation methods for streamflow and groundwater*. Developments in Water Science, 48, Elsevier Science: 139–198.

Hosking J R M (1990) L-moments: analyzing and estimation of distributions using linear combinations of order statistics. *Royal Statistical Society Journal, Series B.* 52: 105–124.

Hosking J R M, Wallis J R (1993) Some statistical useful in regional frequency analysis. *Water Resources Research.* 29: 271–281.

Hosking J R M, Wallis J R (1997) regional frequency analysis, an approach based on L-moments. Cambridge University press, Cmbridge, UK. 224 pp.

Hosking J R M, Wallis J R, Wood E F (1985) Estimation of the Generalized Extreme-Value Distribution by the Method of Probability-Weighted Moments. *Technometrics.* 27(3): 251-261.

Hosking J R M, Wallis J R, Wood E F (1985a). An appraisal of the regional flood frequency procedure in the UK Flood Studies Report. *Hydrological Sciences Journal,* 30(1): 85-109.

Houck M H, Datta B (1981) Performance evaluation of a stochastic optimization model for reservoir design management with explicit reliability criteria. *Water Resources Bulletin*. 17 (4): 827-832.

Hounam C E, Burgosm J J, Kalik M S, Palmer W C, Rodda J C (1975) *Drought and agriculture*, Technical Note No. 138, WMO, Geneva, 127 pp.

Hsu SY, Tung C P, Chen CJ, Wang C (2004) Application to Reservoir Operation Rule-Curves. *Proceedings of World Water and Environmental Resources Congress 2004, ASCE Conference Proceedings*. 138: 304-314.

Hurt C E (2005) *Risk management instruments for water allocation*, OECD editions, Paris. 67 pp.

Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. *Water Resources Management*, 21: 775–788.

IPCC - Intergovernmental Panel on Climate Change (2001) *Climate change 2001: impacts, adaptation and vulnerability*. Contribution of working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 645 pp.

IPCC - Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 982 pp.

Isaaks E H, Srivistava R M (1989), *Applied Geostatistics*, Oxford University Press. 569 pp.

Israel M, Lund J R (1995) Recent California water transfers: implication for water management. *Natural resources journal*. 35: 1-12.

Jaiswal R K, Goel N K, Singh P, Thomas T (2003) L-moment based flood frequency modeling. Journal of the Institution of Engineers. India. 84: 6-10.

Katz R W, Parlange M B, Naveau P (2002) Statistics of extremes in hydrology. Advances in Water Resources 25: 1287–1304.

Kerr R A (2005) Confronting the bogeyman of the climate system. *Science.* 310: 432–433.

Kininmonth W R, Voice M E, Beard G S, de Hoedt G C, Mullen C E (2000) Australian climate services for drought management. In: D A Wilhite (Eds.) *Drought, a global assessment.* Routledge, pp 210-222.

Kogan F N (1995) Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological Society*. 76(5): 655–668.

Kumar R, Chatterjee C, Kumar S, Lohani AK, Singh RD (2003) Development of regional flood frequency relationships using L-moments for Middle Ganga Plains Subzone 1(f) of India. *Water Resources Management.* 17:243–257.

La Calle M (2008) An environmental focus on drought. In: Iglesias A, Cancelliere A, Wilhite DA, Garrote L, Cubillo F (Eds.) *Coping with drought risk in agriculture and water supply systems*. Springer, Netherlands, pp 37-54.

Laaha G, Bloeschl G (2005) Low flow estimates from short stream flow records—a comparison of methods. *Journal of Hydrology.* 306: 264–286.

Laaha G, Bloeschl G (2006) A comparison of low flow regionalisation methods – catchment grouping. *Journal of Hydrology.* 323: 193–214.

Laaha G, Bloeschl G (2007) A national low flow estimation procedure for Austria. *Hydrological Science Journal.* 52: 625–644.

Labadie J W, Brazil L E , Corbu I, Johnson L E (1989) *Computerized Decision Support Systems for Water Managers*. American Society of Civil Engineers, New York. 978 pp.

Lawrance AJ, Kottegoda NT (1977) Stochastic Modeling of Riverflow Time Series. *Journal of the Royal Statistical Society Series A* (General). 140(1): 1-47.

Lise W, Garrido A, Iglesias E (2001) A game model of farmers' demand for irrigations water from reservoirs in southern Spain. *Risk, decision and policy*. 6: 167-185.

Loucks D P (1995) Developing and implementing Decision Support Systems: a critique and a challenge. *Journal of the American Water Resources Association JAWRA*. 31 (4): 571–582.

Loucks D P, Da Costa J R (1991) *Decision Support Systems. Water Resources Planning*. Springer, Berlin. 574 pp.

Loucks D P, Van Beek E (2005) *Water Resources systems Planning and Management: an Introduction to Methods, Models and Applications*. UNESCO Press, Paris.

Luo B, Hang G H, Zou Y, Yin Y (2007) Towards quantifying the effectiveness of water trading under uncertainty. *Journal of environmental management*. 83: 181-190.

Mannucci E (1985) Il miracolo del tubo (The pipe miracle). *Panorama*. 1016: 232-236.

Marsh T, Black A, Acreman M, Elliot C (2000) River flows. In: Acreman M (Eds.) *The Hydrology of the UK: A study of Change*, Routledge, UK. pp 101–130.

Martin Carrasco F J, Garrote L (2007) Drought-induced water scarcity in water resources systems. In Vasiliev O F, van Gelder P H A J M, Plate E J, Bolgov M V (Eds.) Extreme Hydrological Events: New Concepts for Security. *NATO Science Series*. 78 (4): 301-311.

Matalas N C (1963) Probability distribution of low flows. Prof paper 434-A U.S. Geological Survey.

McKee T B, Doeskin N J, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: *Proceedings of the Eighth Conference on Applied Climatology, Anaheim, CA, January 17-23, 1993. American Meteorological Society*. pp 179-184.

McMahon T A (1976) Low Flow analyses of streams: details of computational procedures and annotated bibliography. Monash University, Department of Civil Engineering, Clayton (Australia), Research Report No. 5/1976, 60 pp.

McMahon T A, Diaz Arenas A (1982) Methods of computation of low streamflow. *Paris, UNESCO Studies and reports in hydrology*, vol. 36, pp 107.

MEDROPLAN - Mediterranean Drought Preparedness and Mitigation Planning (2006) *Drought management guidelines*. Executive summary, CIHEAM – IMAZ, Special publication of the Medroplan Project, Spain.

Menedez M (1995) *Aspectos hidrologicos de las Sequias. Las sequias en España (Drought hydrological aspects. Drought in Spain).* Centro de Estudios Hidrograficos del Cedex. Madrid, Spain. 127 pp.

Merz R, Piock-Ellena U, Bloeschl G, Gutknecht D (1999) Seasonality of flood processes in Austria. *IAHS Publication*. 255: 273–278.

Metropolis N (1987) The beginning of the Monte Carlo method. *Los Alamos Science*: 125–130.

Metropolis N, Ulam S (1949). The Monte Carlo Method. *Journal of the American Statistical Association*. 44(247): 335–341.

Modarres R (2007) Regional maximum wind speed frequency analysis for the arid and semi-arid regions of Iran. *Journal of Arid Environments*. 72 (7): 1329-1342.

Modarres R (2008) Regional frequency distribution type of low flow in north of Iran by L-moments. *Water Resources Management.* 22: 823–841.

Munger T T (1916) Graphic method of representing and comparing drought intensities. *Monthly Weather Review*. 44: 642–643.

Nathan R J, McMahon T A (1990) Identification of homogeneous regions for the purpose of regionalisation. *Journal of Hydrology.* 121:217–238.

NDMC - National Drought Mitigation Center (2006) *What is drought?* University of Nebraska – Lincoln, pp 6.

New M, Todd M, Hulme M, Jones P (2002), Precipitation measurements and trends in the twentieth century. International Journal of Climatology, 21: 1899–1922.

Palmer R N, Kutzing S L, Steinemann A C (2002) Developing drought triggers and drought responses: an application in Georgia. *Proceedings of the World Water & Environmental Resources Congress, ASCE, Roanoke, Virginia*.

Palmer W C (1965) *Meteorological drought*. Research Paper No. 45. U.S. Weather Bureau, Washington, DC.

Palmer W C (1968). Keeping track of crop moisture conditions, nationwide. The new Crop Moisture Index. *Weatherwise*. 21: 156-161.

Parida B P, Kachroo R K, Shrestha D B (1998) Regional flood frequency analysis of Mahi-Sabarmati basin (Subzon 3-a) using index flood procedure with L-moments. *Water Resources Management*. 12:1–12.

Petersen M S (1984) *Water resource Planning and Development*. Prentice-Hall, Englewood Cliffs, NJ, pp 316.

Pliefke T, Sperbeck S T, Urban M, Peil U, Budelmann H (2007) A Standardized Methodology for Managing Disaster Risk – An Attempt to Remove Ambiguity. *Proceedings of the 5th International Probabilistic Workshop*, Ghent, Belgium.

Pyrce R (2004) *Hydrological low flow indices and their uses*. Watershed Science Centre Report No. 04-2004. Trent University. Canada. pp.38.

Quenouille M H (1956) Notes on bias in estimation. *Biometrika.* 43: 353–360.

Rassmusson E M, Dickinson R E, Kutzbach J E, Cleaveland M K (1993) Climatology. In: Maidment D R (Ed) *Handbook of Hydrology*. McGraw-Hill Inc., New York: 2.1 - 2.44.

Regione Toscana, Unioncamere Toscana, ISTAT – Istituto Nazionale di statistica (2009) *Annuario Statistico Regionale, Toscana 2008 (Regional statistic yearbook, Toscana 2008)*. Pubblicazioni del Sistema Statistico Regionale.

Reitsma R F (1996) Structure and support of water-resources management and decision-making. Journal of Hydrology. 177 (3-4): 253-268.

Richards K S (1982) *Rivers: form and process in alluvial channels*. London: Methuen. pp 325.

Riggs H C (1973) *Regional analysis of streamflow characteristics.* US Geological Survey Techniques of Water Resources, United States Government Printing office, Washington. VIII+15 pp.

Rivera-Ramirez H D, Warner G S, Scatena F N (2002) Prediction of master recession curves and baseflow recessions in the Luquillo mountains of Puerto Rico. *Journal of the American Water Resources Association*. 38: 693-704.

Rosenthal W, Dozier J (1996). Automated mapping of montane snow cover at subpixel resolution from the Landsat Thematic Mapper. *Water Resources Research*. 32: 115–130.

Rossi F, Fiorentino M, Versace P (1984) Two-component extreme value distribution for flood frequency analysis. *Water Resources Research*. 20(7): 847–856.

Rossi F, Villani P (1994) Regional flood estimation methods. In: Rossi G, Harmancioglu N, Yevjevch V (Eds.) *Coping with Floods*. Applied Sciences, Vol. 257, Kluwer Academic Publishers, Dordrecht, the Netherlands: 135–169.

Rossi G (2000) Drought mitigation measures: a comprehensive framework. In: Vogtand J V, Somma F (Eds.) *Drought and Drought Mitigation in Europe*. Kluwer Academic Publishers, Dordrecht: pp 233-246.

Rossi G (2003a) An integrated approach to drought mitigation in Mediterranean countries. In: Rossi G et al. (Eds.) *Tools for drought mitigation in Mediterranean regions*, Kluwer Academy, pp 3-18.

Rossi G (2003b) Requisite for a drought watch system. In: Rossi et al. (Eds.) *Tools for drought mitigation in Mediterranean regions, Kluwer Academy*, pp.147-157.

Rossi G (2007) Monitoraggio del fenomeno (Risk monitoring). In: Rossi G (Eds.) *Siccità: analisi, monitoraggio e mitigazione. Applicazioni in Sicilia (Drought: analysis., monitoring and mitigation. Applications in region Sicily)*, Nuova Bios, Cosenza, pp 15-48.

Rossi G, Benedini M, Tsakiris G, Giakoumakis S (1992). On regional drought estimation and analysis. *Water Resources Management*. 6: 249-277.

Rossi G, Cancelliere A, Giuliano G (2007b) Chapter 11 Reducing shortage risk of water supply systems under drought conditions. In: La Loggia G, Aronica GT, Ciraolo G (Eds.) *Water Resources Assessment under Water Scarcity Scenarios*. Centro Studi Idraulica Urbana, Milano. pp 221-246.

Rossi G, Castiglione L, Bonaccorso B (2007a) Chapter 16: Guidelines for Planning and Implementing Drought Mitigation Measures. In: Rossi G et al. (Eds.) *Methods and Tools for Drought Analysis and Management*. Netherlands, Springer. pp 325-347.

Rouse J W, Haas R H, Schell J A, Deering D W (1973) Monitoring vegetation systems in the great plains with ERTS. *Third ERTS Symposium.* 351: 309-317.

Saf B (2008) Regional flood frequency analysis using L-Moments for the West Mediterranean Region of Turkey. *Water Resources Management*. 23 (3): 531-551.

Salas J D (1993) Analysis and modeling of hydrologic time series. In: Maidment D (Ed.) *Handbook of Hydrology:* chapter 19. McGraw-Hill, New York.

Santhi C, Allen P M, Muttiah R S, Arnold J G, Tuppad P (2008) Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. *Journal of Hydrology*. 351: 139-153.

Santos J F, Pulido-Calvo I, Portela M M (2010), Spatial and temporal variability of droughts in Portugal, *Water Resources Research*, 46: 1-14.

Sargent D M (1979) Reservoir operating rules for drought conditions. *Hydrological Sciences Journal 24*(1): 83 – 94.

Searcy J K (1959) *Flow duration curves – Manual of hydrology, Part 2. Low flow techniques*. USGS. Water Supply Paper 1542-A.

Sechi G M, Sulis A (2010) Intercomparison of Generic Simulation Models for Water Resource Systems. *Proceedings of International Environmental Modelling and Software Society (iEMSs) 2010 International Congress, Ottawa, Canada.* 10 pp.

SEI Stockholm Environment Institute (2005) WEAP: Water Evaluation And Planning System, User Guide, Somerville, Maryland. 219 pp.

Shafer B A, Dezman L E (1982) Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: *Proceedings of the Western Snow Conference*, Reno, NV, 19-23, April 1982, pp 164-175.

Shepard D (1968) A two-dimensional interpolation function for irregularly-spaced data. *Proceedings of the 1968 23rd ACM national conference. New York, USA*, pp 517-523.

Singh K P, Stall J B (1974) Hydrology of 7-day 10-yr low flows. *Journal of the Hydraulics Division*, HY12: 1753-1771.

Sivapalan M. (2003) Prediction in ungauged basins: a grand challenge for theoretical hydrology. *Hydrological Processes.* 17: 3163-3170.

Smakhtin V Y (2001) Low flow hydrology: a review. *Journal of Hydrology*. 240: 147-186.

Smakhtin V Y, Toulouse M (1998) Relationships between low-flow characteristics of South African streams. Water SA. 24: 107-112.

Stahl K, Hisdal H (2004) Hydroclimatology. In: Tallaksen L M, van Lanen H A J (Eds.) *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater*. Developments in Water Science, 48. Elsevier Amsterdam, pp 133–144.

Stedinger J R (1983) Estimating a regional flood frequency distribution. *Water Resources Research*, 19(2): 503 510.

Svoboda M. (2000) An introduction to the Drought Monitor. *Drought Network News*. 12: 15–20.

Syme G J, Nancarrow B E, Seligman C (2000) The evaluation of information campaigns to promote voluntary household water conservation. *Evaluation review*. 24(6): 539-578.

Tallaksen L M, Madsen H, Clausen B (1997) On the definition and modeling of streamflow drought duration and deficit volume. *Hydrological Sciences Journal*. 42 (1): 15–33.

Tartaglia V, Caporali E, Cavigli E, Moro A (2006) L-moments based assessment of a mixture model for frequency analysis of rainfall extremes. *Advances in Geosciences.* 2: 331–334.

Tasker G D (1987) A comparison of methods for estimating low flow characteristics of streams. Water Resources Bulletin. 23: 1077–1083.

Tsakiris G, Pangalou D (2008) Drought charachterization in the Mediterranean. In: Iglesias A, Cancelliere A, Wilhite DA, Garrote L, Cubillo F (Eds.) *Coping with drought risk in agriculture and water supply systems*. Springer, Netherlands, pp 69-80.

Tsakiris G, Vangelis H (2005) Establishing a Drought Index incorporating evapotranspiration. *European Water*.9(10): 1-9.

Tucci C, Silveira A, Sanchez J, Albuquerque F (1995) Flow regionalisation in the upper Paraguay basin, Brazil. *Hydrological Sciences -Journal des Sciences Hydrologique* 40(4): 485-497.

Tukey J W (1958) Bias and confidence in not quite large samples. *Annals of Mathematical Statistics.* 29: 614.

UN/ISDR - United Nations secretariat of the International Strategy for Disaster Reduction (2007) *Drought Risk Reduction Framework and Practices*. Geneva, Switzerland, 98+VI pp.

UN/ISDR - United Nations secretariat of the International Strategy for Disaster Reduction (2009) *Terminology on Disaster Risk Reduction*. Geneva, Switzerland, 31+IV pp.

Vicente-Serrano S M, Gonzalez-Hidalgo J S,Luis M, Raventos J (2004) Drought patterns in the Mediterranean area: The Valencia region (eastern Spain), *Climate Research*, 26: 5– 15.

Viglione A, Claps P, Laio F (2006) Utilizzo di criteri di prossimità nell'analisi regionale del deflusso annuo (Use of proximity criteria for the regional analysis of annual flow). *Proceedings of: XXX° Convegno di Idraulica e Costruzioni Idrauliche, Roma*.

Vogel R M, Fennessey N M (1994) Flow–Duration Curves: new interpretation and confidence intervals. *Journal of Water Resources Planning and Management*. 120(4): 485-504.

Vogel R N, Kroll C N (1989) Low flow frequency analysis using probability plot correlation coefficients. *Journal of Water resources planning and management*. 115(3): 338 – 357.

Vogel R M, Kroll C N (1992) Regional Geohydrologic-Geomorphic relationships for the estimation of low-flow statistics. *Water Resources Research*. 28(9): 2451-2458

Vogt J, Somma F (2000) *Drought and drought mitigation in Europe*, Kluwer academic publishers. The Nederlands, pp 197.

Werick WJ (1993) National study of water management during drought: results-oriented water resources management. In: Hon K (Ed.) *Water Management in the 90's*. ASCE, New York. pp 445–450.

White G F (1969) Strategies for American water management, University of Michigan Press, Ann Arbor, Michigan. pp IX + 155.

Wilhite D A (1991) Drought Planning: a process for state government. *Journal of the American Water Resources Association (JAWRA)*. 27(1): 29-38.

Wilhite D A(1993) *Drought Assessment, Management and Planning: Theory and Case Studies*. Kluwer, Dordrecht-Boston-London. pp XIV + 393.

Wilhite D A (2008) Drought Monitoring as a Component of Drought Preparedness Planning. In: Iglesias A, Cancelliere A, Wilhite D A, Garrote L, Cubillo F (Eds.) *Coping with drought risk in agriculture and water supply systems*. Springer, Netherlands, pp 3-19.

Wilhite D A, Glantz M H (1985) Understanding the drought phenomenon: The role of definitions. *Water International*. 10: 111–120.

Wilhite D A, Hayes M J, Knutson C, Smith K H (2000) Planning for drought: moving from crisis to risk management. *Journal of the American Water Resources Association (JAWRA)*. 36(4): 697–710.

Wolman M G, Miller J P (1960) Magnitude and frequency of forces in geomorphic processes. *Journal of geology*. 68: 54–74.

Wurbs R (1993) Reservoir-system simulation and optimization models. *Journal of Water Resources Planning and Management*. 119(4): 455–472.

Yeh W (1985) Reservoir management and operations models: A state of the art review. *Water Resources Research.* 21(12): 1797–1818.

Yevjevich V, Hall W A, Salas J D (1978) *Drought Research Needs*. Water Resources Publication, Fort Collins, Colorado. 276 pp.

Yulianti J S, Burn DH (1998) Investigating links between climatic warming and low streamflow in the Prairies region of Canada. *Canadian Water Resources Journal*, 23: 45-60.

Zaidmann MD, Keller V, Young A R, Cadman D (2003) Flow-duration-frequency behaviour of British rivers based on annual minima data. *Journal of Hydrology*. 277: 195–213.

Zelenhasić E, Salvai A (1987) A Method of Streamflow Drought Analysis. *Water Resources Research*, 23(1), 156-168.

APPENDIX A - DISCHARGE GAUGES DATASET

Code	Name	X-UTM	Y-UTM	1st year of registration	Years of registration	Catch-ment area	Qmean	Qmax	Q70	Q90	Qmin	Q(7,2)
		m	m			km²	m³/s	m³/s	m³/s	m³/s	m³/s	m³/s
4005	Carrara	590504	4880917	2004	5	6.9	1.266	222.114	0.043	0.000	0.000	0.037
4010/4011	Canevara/Canevara aut	593571	4879012	1950	20	46.0	4.093	194.708	0.862	0.465	0.000	0.456
4017	Ruosina	601760	4872316	2004	4	28.6	1.456	35.197	0.357	0.239	0.043	0.786
4045	Ponte Tavole auto	595126	4869693	2000	8	86.4	5.525	85.909	1.264	0.426	0.084	0.706
4059	Camaiore_auto	602375	4864625	2000	6	48.4	0.533	12.336	0.202	0.050	0.003	0.028
4070	Quiesa	610300	4857600	1974	29	0.0	0.131	0.553	0.088	0.054	0.012	0.059
4115	Camporgiano auto	607120	4891013	2001	6	180.6	29.219	272.078	0.929	0.256	0.000	0.361
4165	Ponte di Campia auto	616336	4882954	2002	7	474.7	8.947	941.930	0.588	0.018	0.002	0.365
4195	Calavorno auto	622706	4875385	1996	11	706.3	10.198	354.159	3.317	2.416	1.512	2.462
4200	Ponte a Bussato	625644	4878646	1953	14	29.0	1.371	56.916	0.476	0.250	0.072	0.249
4231	Ponte di Lucchio auto	637634	4878364	2003	6	169.4	18.058	221.207	5.960	2.082	0.163	1.772
4255	Chifenti auto	625375	4873875	2004	5	314.7	7.214	188.512	0.543	0.300	0.066	0.263
4284	Piaggione auto	621729	4865216	2000	8	1163.3	16.284	400.448	4.183	2.229	1.870	2.594
4286	Mutigliano auto	619306	4859999	1998	8	49.0	0.658	31.708	0.243	0.100	0.000	0.195
4291	Monte S. Quirico auto	621183	4857323	2004	5	1251.7	31.248	441.602	8.926	5.744	0.999	4.989
4365	Vecchiano auto	612631	4848657	2004	5	1324.3	50.699	865.792	26.766	21.161	10.951	21.194
4379/4380	Stia/Stia auto	717163	4853952	1942	31	62.0	1.341	148.000	0.327	0.120	0.000	0.114
4410/4411	Subbiano/Sub auto	731639	4828387	1936	36	738.0	16.588	1190.000	3.030	0.960	0.000	0.970
4520/4521	Ponte Fer Fi-Rm/ Ponte Fer Fi-Rm auto	728547	4816717	1954	35	1272.0	6.184	339.175	0.660	0.264	0.043	0.230

continued

Code	Name	X-UTM	Y-UTM	1st year of registration	Years of registration	Catch-ment area	Qmean	Qmax	Q70	Q90	Qmin	Q(7,2)
		m	m			km²	m³/s	m³/s	m³/s	m³/s	m³/s	m³/s
4568	Bucine auto	711932	4817927	1996	12	170.7	1.310	56.764	0.118	0.027	0.005	0.021
4571	Montevarchi auto	707396	4824276	2002	7	2670.0	18.847	787.917	1.929	1.084	0.607	0.987
4591	Ponte di Incisa Vald auto	697982	4840564	2002	7	3079.0	24.158	808.940	3.332	1.926	0.000	1.795
4610	Ponte del Bilancino	683511	4871946	1965	18	150.0	3.007	231.000	0.400	0.110	0.010	0.076
4623	Carza auto	686400	4870147	2003	6	66.31	1.066	38.780	0.191	0.039	0.003	0.124
4640/4641	Fornacina/Fornac auto	698589	4852958	1960	42	831.0	13.343	917.000	2.991	1.078	0.220	0.873
4659/4660	Nave di Rosano /Nave di Rosano auto	695524	4849512	1931	41	4083.0	49.706	3368.500	9.149	4.076	0.000	3.100
4679	Firenze Uffizi auto	681542	4848770	1992	12	4237.0	57.268	4946.100	7.996	1.812	0.000	0.614
4710	Ponte dei Falciani	678600	4838200	1938	21	120.0	0.800	98.125	0.083	0.015	0.000	0.012
4723	Tavarnuzze auto	678682	4842330	1997	11	142.0	0.754	26.821	0.122	0.023	0.000	0.004
4779/4780	Gamberame auto/Gamberame	670839	4865710	1960	38	150.0	3.730	165.000	0.850	0.374	0.080	0.325
4782	Prato auto	669338	4860597	2004	4	166.7	3.325	69.065	0.769	0.185	0.017	1.591
4791	S Piero a Ponti auto	671475	4852459	1992	15	246.1	3.902	256.515	0.551	0.175	0.011	0.134
4811	Ponte a Signa auto	668764	4848763	2002	7	4536.1	40.021	847.627	8.456	4.993	0.000	4.960
4860	Burgianico	653321	4869208	1986	27	13.0	0.305	16.300	0.048	0.017	0.003	0.014
4875	Poggio a Caiano auto	665870	4853523	1992	15	435.0	7.273	288.565	2.147	1.193	0.043	0.852
4901	Brucianesi automatica	664993	4847525	2002	5	5463.0	45.400	1154.900	15.486	8.556	5.081	10.471
4910	Sambuca	679300	4826104	1973	26	119.0	1.015	70.060	0.123	0.027	0.007	0.020
4965	Poggibonsi automatica	672233	4815392	2004	5	177.9	2.473	83.323	1.099	0.682	0.416	0.862
4970	Castelfiorentino	659024	4829794	1960	18	806.0	5.539	406.000	2.249	1.530	0.600	1.688
5001	Ponte di Fucecchio auto	646047	4842510	2004	4	6877.0	62.749	1454.000	13.916	8.754	7.641	9.746

continued

Code	Name	X-UTM	Y-UTM	1st year of registration	Years of registration	Catch-ment area	Qmean	Qmax	Q70	Q90	Qmin	Q(7,2)
		m	m			km²	m³/s	m³/s	m³/s	m³/s	m³/s	m³/s
5005	Fornacino auto	649284	4832777	2004	5	70.6	0.301	18.336	0.023	0.006	0.002	0.038
5040	Colonna	645489	4860320	1954	34	32.5	0.557	19.424	0.040	0.000	0.000	0.000
5050	Molino Parlanti	645604	4860168	1976	26	0.81	0.070	0.840	0.030	0.007	0.000	0.006
5130/5131	Capannoli/Capan auto	636375	4827125	1963	29	337.0	3.138	208.000	0.210	0.058	0.008	0.046
5161	Belvedere auto	632090	4833179	2001	6	516.3	3.902	318.751	1.141	0.615	0.000	0.830
5190	S. Giovanni alla Vena	627809	4838074	1933	32	8186.0	79.325	1696.600	16.477	7.100	0.466	5.955
5231	Pisa a Sostegno auto	612128	4841120	1992	11	8224.0	81.309	1706.700	118.933	102.982	54.513	92.138
5345	Rosignano 1 auto	616460	4806336	2004	5	6.1	2.652	4.119	2.306	2.088	1.659	2.070
5372	Masso degli Specchi auto	658511	4796163	2003	6	132.7	1.057	64.987	0.039	0.010	0.001	0.008
5400/5401	Ponte di Monterufoli/ P. di Monterufoli auto	635505	4798239	1971	26	634.0	4.405	311.027	0.224	0.033	0.000	0.032
5448	Venturina	629972	4765961	1985	18	4.3	0.129	0.519	0.073	0.048	0.020	0.051
5460	Molino del Balzone	639807	4775444	1976	27	58.0	0.451	43.274	0.018	0.000	0.000	0.000
5470/5471	Ponte per Montioni/ Ponte per Montioni auto	639460	4770314	1990	14	195.0	1.894	237.065	0.075	0.009	0.000	0.007
5485	Calzalunga auto	640286	4769745	1997	11	99.1	0.277	25.026	0.005	0.000	0.000	0.000
5510	Ponte Statale Aurelia	631568	4764201	1974	21	356.0	2.837	396.400	0.000	0.000	0.000	0.000
5601	Macchiascandona	663574	4741318	2004	5	605.7	2.762	215.517	0.319	0.175	0.038	0.128
5610	Lepri	666332	4752087	1955	19	229.0	2.012	130.05	0.638	0.36	0.115	0.283
5710	Ornate	687096	4777010	1934	5	483.0	8.236	339.692	1.949	1.483	0.762	2.468
5720	Ponte di Torniella	674464	4772230	1974	29	70.0	0.752	61.633	0.058	0.021	0.006	0.021
5760	Monte Amiata Scalo	707682	4761272	1936	8	580.0	3.667	141.550	0.250	0.061	0.008	0.066

continued

Code	Name	X-UTM	Y-UTM	1st year of registration	Years of registration	Catch-ment area	Qmean	Qmax	Q70	Q90	Qmin	Q(7,2)
		m	m			km²	m³/s	m³/s	m³/s	m³/s	m³/s	m³/s
5790/5791	Sasso d'Ombrone/ Sasso d'Ombrone auto	689504	4756206	1933	33	2657.0	19.489	1022.100	3.639	1.857	0.262	1.487
5940	Cavallina	596306	4732483	1974	9	5.2	0.046	1.740	0.007	0.002	0.000	0.001
5950	S. Mamiliano	601085	4733816	1974	9	6.7	0.066	7.199	0.003	0.000	0.000	0.000
5960	Molino Giglio	655094	4692259	1974	6	2.3	0.008	0.512	0.001	0.001	0.000	0.001